Transmission Expansion Planning in Deregulated Power Systems

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To my Parents

Contents

1 Introduction

1.1 Research Motivations

Transmission system is one of the major components of the electric power industry. In deregulated power systems, transmission system provides the required environment for competition among power market participants. Therefore as electric loads grow, transmission expansion planning should be carried out in timely and proper way to facilitate and promote competition.

The main objective of power system planning in regulated power systems is to meet the demand of loads, while maintaining power system reliability. In this environment uncertainty is low. Transmission expansion planning is centralised and coordinated with generation expansion planning. Planners have access to the required information for planning. Therefore, planners can design the least cost transmission plan based on the certain reliability criteria [1].

Restructuring and deregulation have unbundled the roles of network stakeholders [2]. Unbundling the roles has brought new challenges for stakeholders. Stakeholders have different desires and expectations from the performance and expansion of the system. Therefore, new incentives and disincentives have emerged regarding transmission expansion decisions. Providing non-discriminatory access, facilitating competition, minimizing the risk of investments, minimizing the costs of investment and operation, increasing the reliability of the network, increasing the flexibility of operation, reducing network charges, and minimizing environmental impacts are desires of different system stakeholders in transmission expansion. These desires have different degrees of importance from the viewpoint of different stakeholders. On the other hand, stakeholders have different degrees of importance in decision making on transmission planning. Planners must consider the importance degrees of stakeholders and their desires in transmission expansion planning.

In deregulated power systems participants take their decisions independently. They change their strategies frequently to acquire more information from the market to maximize their benefits. Consumers adjust their loads according to the price signals. Availability of independent power producers is uncertain. Wheeling powers are time varying and affect the nodal prices of the control areas that they pass through. Transmission expansion planning is not coordinated with generation expansion planning. Hence, there is not a specified pattern for load and dispatched power in deregulated power systems. Due to these uncertainties expansion of transmission networks have been faced with great risks in deregulated environments. Therefore, the final plan must be selected after the risk assessment of all solutions. Since risk assessment is characteristically based on probabilistic and stochastic methods, probabilistic methods should be developed for transmission planning in deregulated power systems.

1.2 Research Objectives

Restructuring and deregulation of power industry have changed the objectives of transmission expansion planning and increased the uncertainties. Due to these changes, new approaches and criteria are needed for transmission planning in deregulated power systems. The objective of this research work is to present a new approach for transmission expansion planning with considering new objectives and uncertainties in deregulated power systems. The approach must take into account the desires of all stakeholders in transmission expansion planning. Market based criteria must be defined to achieve the new objectives. Combination of market based criteria, technical criteria and economical criteria must be used for measuring the goodness of expansion plans to achieve market requirements, technical requirements, and economical requirements altogether.

1.3 Thesis Overview

This thesis is organized as follows. In chapter 2, state of the art review on transmission expansion planning approaches is presented and the problem is defined in detail. In chapter 3, a probabilistic method for computing probability density functions of nodal prices is presented. Market based criteria are defined in chapter 4. A market based transmission expansion planning approach with conventional risk assessment is presented in chapter 5. Shortages of conventional risk assessment method are stated in chapter 6 and a fuzzy method for risk assessment is presented in this chapter. In chapter 7, a market based transmission expansion planning approach with consideration given to stakeholders' desires is presented. The presented approach in chapter 7 is extended to takes into account non-random uncertainties and vague data in section 8. Conclusions in section 9 close the thesis.

2 Transmission Expansion Planning Approaches

Restructuring and deregulation of the power industry have changed the objectives of transmission expansion planning and increased the uncertainties. Due to these changes, new approaches and criteria are needed for transmission expansion planning in deregulated power systems. Review of the presented approaches and discussion of their advantages and drawbacks helps the procedure of presenting new approaches and criteria for transmission planning in deregulated environments. State of the art review on transmission expansion planning approaches is presented in this chapter [3].

This chapter is organized as follows. In section 2.1, current literature on transmission expansion planning approaches is reviewed. The problem of transmission expansion planning in deregulated power systems is defined in section 2.2.

2.1 Literature Survey: State of the art

Transmission expansion planning approaches can be classified from different viewpoints. From the viewpoint of power system uncertainties, transmission expansion planning approaches can be classified in:

- deterministic, and
- non-deterministic approaches.

In deterministic approaches the expansion plan is designed only for the worst cases of the system without considering the probability of occurrence (degree of occurrence) of them. In non-deterministic approaches the expansion plan is designed for all possible cases which may occur in future with considering the occurrence probability of them. Hence, Non-deterministic approaches are able to take into account the past experience and future expectations. Non-deterministic approaches are explained in subsection 2.1.1 more in detail.

From the viewpoint of power system horizons, transmission expansion planning approaches can be classified in:

- static, and
- dynamic approaches.

In static planning the planner seek the optimal plan for a single year on the planning horizon, that is, planner answer only to the questions “what” transmission facilities must be added to the network and “where” they must be installed. In dynamic planning multi year is considered and planners seek the optimal strategy along the whole planning period. On the other word, in dynamic planning in addition to “what” and “where” planners answer to the question “when” the transmission facilities must be installed in planning horizon.

From the viewpoint of power system structures, transmission expansion planning approaches can be classified in transmission expansion planning approaches for:

- regulated, and
- deregulated power systems.

The main objective of expansion planning in regulated power systems is to meet the demand of loads, while maintaining reliability and service quality of power system. In this environment uncertainty is low. Transmission expansion planning is centralised and coordinated with generation expansion planning. Planners have access to the required information for planning. In these systems location of loads and generations, size of loads and generating units, availability of units, load pattern, and dispatch pattern are known. Therefore, planners can design the least cost transmission plan based on the certain reliability criteria. Transmission planning in regulated systems is modelled with a deterministic optimization. The objective function is cost of planning and operation, with technical and economical constraints. In general this optimization is a nonlinear mixed-integer constraint optimization. Different mathematical and heuristic approaches have been proposed to solve this problem [1].

Deregulation has changed the objective of transmission expansion planning and increased the uncertainties of power systems. Due to these changes, new approaches are needed for transmission expansion planning. The goal of this dissertation is to present a transmission expansion planning approach for deregulated environments. Hence, here the publications on non-deterministic transmission expansion planning approaches and transmission expansion planning approaches for deregulated environments are reviewed [3]. The bibliographies of the publications on transmission expansion planning approaches for regulated environments are presented in [1].

2.1.1 Non-deterministic Transmission Expansion Planning Approaches

Uncertainties can be classified in two categories:

- Random, and
- non-random uncertainties.

Random uncertainties are deviation of those parameters which are repeatable and have a known probability distribution. Hence, their statistics can be derived from the past observations. Uncertainty in load is in this category. Non-random uncertainties are evolution of parameters which are not repeatable and hence their statistics cannot be derived from the past observations. Uncertainty in generation expansion is in this category. Besides the uncertainties, there are imprecision and vague data in expansion planning. Imprecision and vague data are the data which can not be clearly expressed. Importance degree of different criteria in multi objective planning falls in this category.

Non-deterministic approaches which have been used for transmission expansion planning are:

- probabilistic load flow,
- probabilistic based reliability criteria,
- scenario technique,
- decision analysis, and
- fuzzy decision making.

Probabilistic load flow and probabilistic based reliability criteria approches take into account random uncertainties. Scenario technique considers the non-random uncertainties. Decision analysis is a proper method for dynamic programming. Fuzzy decision making considers imprecision and vague data.

2.1.1.1 Probabilistic Load Flow

Probabilistic load flow is used for network analyzing and expansion planning of regulated power systems. Probabilistic load flow is similar to ordinary load flow, except it gets the probability density functions (PDFs) of loads as input and computes the PDFs of output variables [4]-[7]. This can be accomplished by Monte Carlo simulation, analytical methods and combination of them. PDFs of loads can be estimated based on load prediction and uncertainty analysis [8]. To reduce the computations, power flow equations are linearized around the expected value region and then convolution technique is used for computing the PDFs of outputs. The algorithm of transmission expansion planning using probabilistic load flow is as below [9]-[11]:

- Run the probabilistic load flow for the existing network and given PDFs of loads for the planning horizon, and compute the technical criteria such as the probability of violating line flow limits and voltage limits.
- Suggest some expansion plans based on the computed technical criteria.
- Add each of the suggested plans to the network separately, run the probabilistic load flow, and compute the technical criteria for each plan.
- Select the final plan based on the technical criteria and economic analysis.

2.1.1.2 Probabilistic Based Reliability Criteria

The algorithm of transmission expansion planning using probabilistic based reliability criteria is as bellow [12]-[13]:

- Suggest some expansion plans by analyzing the existing network.
- Add each of the suggested expansion plans to the network separately, and compute the reliability criteria such as expected energy not supplied, expected number of load curtailment, and expected duration of load curtailments for each plan using Monte Carlo simulation.
- Select the final plan based on the reliability criteria and economic analysis.

2.1.1.3 Scenario Technique

Scenario technique and decision analysis are more general and can be used for the planning of any system. The algorithm of expansion planning using scenario techniques is as below [14]-[22]:

- Determining the set of probable future scenarios. A scenario is a set of outcomes or realizations of all uncertainties. The scenarios must be defined so that to cover all non-random uncertainties.
- Determining the occurrence probability or occurrence degree of future scenarios.
- Determining the set of possible solutions (expansion plans).
- Selecting a cost function to measure the goodness of expansion plans.
- Selecting the final plan using one of the following criteria:

    1. Expected cost criterion: this criterion selects the plan that minimizes the expected cost over different scenarios [14]-[16], [19], [22], i.e.:

$$\underset{k}{Min}\ E^k = \sum_l \upsilon^l f^{k,l} \tag{2.1}$$

with:

E^k	expected cost of plan k
υ^l	occurrence degree of scenario l
$f^{k,l}$	cost of plan k in scenario l

2. Minimax regret criterion (risk analysis): in risk analysis the best solution is determined by minimizing the regret [14]-[22]. Regret is a measure of risk. Regret of plan k in scenario l is defined as difference between the cost of plan k in scenario l and cost of the optimal plan of scenario l, i.e.:

$$r^{k,l} = f^{k,l} - f^{op,l} \tag{2.2}$$

with:

$r^{k,l}$	regret of plan k in scenario l
$f^{op,l}$	cost of the optimal plan of scenario l

In risk analysis the plan that minimizes the maximum weighted regret over all future scenarios is selected as the final plan, i.e.:

$$\underset{k}{Min}\left\{\underset{l}{Max}\left(\upsilon^l r^{k,l}\right)\right\} \tag{2.3}$$

3. Laplace criterion: according to this criterion the plan that minimizes the sum of costs over all scenarios is selected as the final plan [14].
4. Von Neumann-Morgenstern criterion: this criterion is extremely pessimist and believes that the most unfavorable scenario is bound to occur [14]. According to this criterion the plan that minimizes the maximum cost over all scenarios is selected as the final plan, i.e.:

$$\underset{k}{Min}\left\{\underset{l}{Max}\left(f^{k,l}\right)\right\} \tag{2.4}$$

Alternatively, an extremely optimist criterion can be also used for selecting the final plan, i.e.:

$$\underset{k}{Min}\left\{\underset{l}{Min}\left(f^{k,l}\right)\right\} \tag{2.5}$$

5. Hurwicz criterion: the plan that minimizes a convex combination of the extremely pessimist solution and the extremely optimistic solution is selected as the final plan [14].
6. Pareto-optimal criterion: a plan is Pareto-optimum if it is not dominated by any other plan. Plan X is dominated by plan Y if its cost is more than the cost of plan Y in all scenarios [19]. This criterion is suitable for eliminating the worst solutions.
7. Robustness criterion: a plan is robust in a scenario, if its regret is zero in this scenario. According to this criterion, a plan is acceptable if it is robust at least in η% of the scenarios [15]-[16], [19].
8. β-robustness criterion: according to this criterion a plan is acceptable if its overcost with respect to the related optimal plan does not exceed β% in each scenario [19].

An example for scenario technique criteria is given in appendix A. The following conclusions can be drawn from the comparison of scenario technique criteria:

- For using expected cost, the basic assumptions of probability must hold, i.e. the scenarios must be repeatable and the laws governing the phenomena remain unchanged, so that the frequency of occurrence of each scenario tends to be close to the probability value assigned to it [15]-[16].
- The expected cost criterion is an *a priori* evaluation i.e. the final solution is chosen before knowing which future scenario occurs, whereas the minimax regret is an *a posteriori* evaluation i.e. the final solution is chosen after assessing the consequence of each solution in each given future scenario [15]-[16].
- Expected cost uses L_1 metric, and minimax regret uses L_∞ metric [15]-[16], [19].
- Expected cost may be blind to solutions that are interesting to be considered in an uncertain environment [15]-[16].
- Expected cost tends to recommend, in many cases, riskier decisions [15]-[16], [19].
- Number of scenarios can be reduced by carrying out a sensitivity analysis in order to discard the uncertainties with little influence on the final result [14].
- For very important decisions, where surviving under an unlikely but catastrophic scenario is needed, it is wise to use the minimax regret as a further test [14].
- In dynamic planning, scenario technique may lead to incoherent successive decisions [14].

2.1.1.4 Decision Analysis

In decision analysis planners try to find the most flexible plan for dynamic planning. The flexibility is defined as the ability of adapting the designed expansion plan to the possible future changes quickly and at reasonable cost [14], [21], [23]. In this method, the entire set of scenarios over different periods of planning horizon is described by an event tree [14], [24]. This tree has two types of nodes: decision nodes and event nodes. The event tree starts from a decision node. Decisions are taken at decision nodes. The branches that emanate from each decision node show the feasible decisions that can be taken at this node. Each of these branches is associated with the cost of correspondent decision and ended to an event node. The branches that emanate from each event node show the probable events that may occur and are associated with the probability of occurring. In fact a scenario is a complete path between the tree root and a final node. The procedure of finding the optimal decision over the entire planning period is a classical stochastic dynamic programming. To determine the optimal first decision, start from the end of event tree, compute the expected cost of each path from the end nods till penultimate decision nods, select the minimum cost strategy at each penultimate decision node and continue to reach the first decision node. The optimal first decision is the minimum cost strategy at the first decision node. Decision analysis leads to the easiest adaptation to the future events. An example for decision analysis is given in appendix B.

2.1.1.5 Fuzzy Decision Making

Fuzzy decision making was developed to model imprecision and vague data. Therefore, it can be used in order to consider vagueness of deregulated power systems in expansion planning [25]-[26]. Fuzzy decision making approach can be summarized in the following steps [27]:

- Representation of the decision problem
    - Identification of decision alternatives set
    - Identification of decision criteria set
- Fuzzy set evaluation of the decision alternatives
    - Selection of preference ratings sets for importance weights of decision criteria and for appropriateness degrees of decision alternatives versus decision criteria
    - Determination of importance weights of decision criteria and appropriateness degrees of decision alternatives versus decision criteria
    - Computing fuzzy appropriateness index by aggregating importance weights of decision criteria and appropriateness degrees of decision alternatives

- Selection of the optimal alternative
    - Prioritization of the decision alternatives by ranking fuzzy appropriateness indices
    - Selection of the decision alternative with highest priority as the optimal alternative

2.1.2 Transmission Expansion Planning Approaches for Deregulated Power Systems

From the viewpoint of transmission planner, there are two major differences between transmission expansion planning in regulated and deregulated environments:

- Objectives of transmission expansion planning in deregulated power systems differ from those of the regulated ones.
- Uncertainties in deregulated power systems are much more than in regulated ones.

In this section objectives of transmission expansion planning in deregulated power systems and uncertainties in deregulated power systems are discussed.

2.1.2.1 Objectives of Transmission Expansion Planning in Deregulated Power Systems

In general, the main objective of transmission expansion planning in deregulated power systems is to provide a non-discriminatory competitive environment for all stakeholders, while maintaining power system reliability. Specifically, the objective of transmission expansion planning is providing for the desires of stakeholders. The desires of stakeholders in transmission expansion are:

- encouraging and facilitating competition among electric market participants [18], [22], [28]-[32],
- providing non-discriminatory access to cheap generation for all consumers [18], [22], [30], [33], [35],
- minimizing the risk of investments against all uncertainties [15]-[21], [24], [28], [36]-[40],
- minimizing the costs of investment and operation [2], [20]-[21],
- increasing the reliability of the network [2], [37]-[38], [41]-[46],
- increasing the flexibility of system operation [2],
- reducing network charges [2],
- minimizing the environmental impacts [2], [18], and
- increasing the value of the system [12], [17], [36], [41]-[46].

The above objectives have different degrees of importance from the viewpoint of different stakeholders. On the other hand, stakeholders have different weights of importance in decision making on transmission expansion. These must be considered by transmission planners [2]. Therefore, new criteria and methods are needed for transmission expansion planning in deregulated power systems.

2.1.2.2 Uncertainties and Vagueness in Deregulated Power Systems

Development of competitive electric markets has introduced significant uncertainties and vagueness in transmission expansion planning. Since methods of modelling random uncertainties, non-random uncertainties, and vagueness are different, power system uncertainties and vagueness must be identified and classified clearly before planning. Sources of random uncertainties in deregulated power systems are:

- load [1], [17]-[21], [38], [47]-[49],
- generation costs and consequently bid of generators [1], [20]-[21], [23], [47], [50]-[51],
- power and bids of independent power producers (IPPs) [30],
- wheeling transactions and power transactions with other areas [19], [23], [36], [49],and
- force outage of generators, lines and other system facilities [1], [18], [20]-[21], [39], [43]-[44], [46], [50].

Sources of non-random uncertainties are:

- generation expansion or closure [1], [17]-[21], [23], [28]-[29], [36]-[39], [48]-[49], [52]-[56],
- load expansion or closure [1], [18], [57],
- installation, closure or replacement of other transmission facilities [1], [18], [23],
- transmission expansion costs [17]-[18], [41], and
- market rules [19], [38].

There is vagueness in the following data:

- occurrence degree of possible future scenarios [2],
- importance degree of stakeholders in decision making [2], and
- importance degree of planning desires from the viewpoint of different stakeholders [2].

Uncertainties in deregulated environments have increased uncertainty in required capacity for transmission expansion and consequently increased the risk of fixed cost recovery [18], [22]. Therefore, incentives for investing in transmission expansion have reduced and caused a delay on transmission planning [38]. Hence, the issue of providing required incentives for investors to invest in transmission expansion and finding a fair mechanism for recovering the fixed costs is a problem in deregulated power systems [51], [58]. In order to use the existing transmission capacities optimally and postpone investment in new transmission facilities, congestion management is being increasingly used in deregulated environments [59]-[62].

Planner can reduce the risk of transmission expansion by developing hedges. Hedging is a technique for reducing risk by generating new alternatives [19], [59]. In fact hedges reduce the risk by reducing number or occurrence degree of the scenarios in which a plan is regrettable, or by reducing the regret of plans in adverse scenarios. The process of considering hedge in transmission expansion planning is described in the following steps [19]:

- Measure the risk of each expansion plan. If there is a robust plan or the vulnerability is low, further effort is not needed.
- Measure exposure, i.e. identify the scenarios in which the most robust plans are regrettable.
- Identify hedging options.
- Incorporate hedging options in the set of expansion plans and return to step 1.

The process continues until finding a low risk plan.

Transmission expansion planning in deregulated power systems can be classified in:

- centralized, and
- decentralized methods [19], [63].

In both methods it is assumed that transmission expansion planning is not coordinated with generation expansion planning. In centralized method transmission expansion decisions is made by a central entity e.g. independent system operator (ISO). In decentralized method transmission expansion can be made by different investors based on their estimation from rate of return on investment. A general overview of the transmission expansion planning schemes used in countries England & Wales, Argentina, Brazil, Chile, Colombia, and Spain is presented in [63]. The comparison of the transmission expansion planning schemes is difficult since the characteristics of electric markets are different.

2.2 Problem Definition

Although many approaches have been presented for transmission expansion planning under uncertainties, none of them considers both random and non-random uncertainties. Moreover they do not consider vagueness in transmission expansion planning. A few approaches have been presented for transmission expansion planning in deregulated environments. The presented approaches do not take into account all new objectives of transmission expansion planning. None of them tries to facilitate and promote competition by expansion planning. They do not consider the interests of all power system stakeholders in expansion planning. In [2] an approach is presented to consider the interests of power system stakeholders in transmission planning. The approach does not consider the competition which is one of the most important objectives of transmission expansion planning in deregulated power systems. In addition the approach is deterministic and does not consider uncertainties and vagueness.

The main goal of this dissertation is to present a centralized static approach for transmission expansion planning in deregulated power systems. The presented approach must take into account all above mentioned stakeholders' desires in transmission expansion planning.

Planning desires have different degrees of importance from the viewpoint of different stakeholders. On the other hand, stakeholders have different weights of importance in decision making on transmission expansion. These must be taken into account in transmission planning by presented approach.

The presented approach must also take into account all above mentioned random uncertainties, non-random uncertainties, and vagueness in transmission planning.

Since the structures of deregulated power systems are different, a deregulated power system with specified structure must be considered as reference model. In this thesis, Pennsylvania - New Jersey - Maryland (PJM) power system is selected as the reference model [62], [64]. It is assumed that PDFs of all input variables which have random uncertainties are given for the peak load of planning horizon including:

- PDF of load of each consumer,
- PDF of bid of each generator and IPP,
- PDF of maximum accessible power of each IPP, and
- PDF of active power of each tie-line.

PDFs of random inputs can be determined based on prediction and uncertainty analysis [8]. The emphasis of this dissertation is on solving the restrictions of transmitting active power by transmission expansion planning. The main contribution of this research work is:

1) ***Presenting a probabilistic tool for analyzing the electric market and suggesting expansion plans base on market bottlenecks.***

2) ***Defining probabilistic market based criteria for transmission expansion planning in deregulated power systems.***

3) ***Presenting an approach for transmission expansion planning using above probabilistic tool and criteria. The approach must take into account all stakeholders' desires, uncertainties, and vagueness of deregulated power systems.***

3 Probabilistic Locational Marginal Prices

In regulated power systems, probabilistic load flow is used to model the random uncertainties in transmission expansion planning [9]-[11]. Probabilistic load flow computes PDFs of line flows and bus voltages based on PDFs of loads. In regulated power systems transmission expansion planning is carried out based on the technical criteria such as probability of violation line flow limits and bus voltage limits. In deregulated power systems in addition to the technical criteria, market based criteria are needed to achieve the objectives of transmission expansion planning in deregulated power systems. Therefore, it is needed to compute the PDFs of variables which show the performance of electric market. This thesis proposes to use PDFs of nodal prices for assessing electric market performance. In this chapter a probabilistic tool for computing PDFs of nodal prices is introduced [67]-[68].

This chapter is organized as follows. In section 3.1, the concept of locational marginal prices is described and a mathematical model for computing nodal prices is presented. In section 3.2, a probabilistic tool, which is named “probabilistic locational marginal prices”, is presented for electric market analysis. The presented approach is applied to an 8-bus network in section 3.3.

3.1 Locational Marginal Prices

Nodal pricing is a pricing system for purchasing and selling electric energy in deregulated power systems. In nodal pricing a price is determined for each transmission node or bus. In this pricing system, all consumers purchase energy at the price of their load bus and all producers sell energy at the price of their generator bus. By definition nodal price or locational marginal price (LMP) is equal to the "cost of supplying next MW of load at a specific location, considering generation marginal cost, cost of transmission congestion, and losses" [62], [64]. Cost of marginal losses is not implemented currently. Figure 3.1 shows the components of LMP. On the other word, LMP of bus i is the additional cost for providing 1 MW additional power at this bus. The marginal cost of providing electric energy at a specific

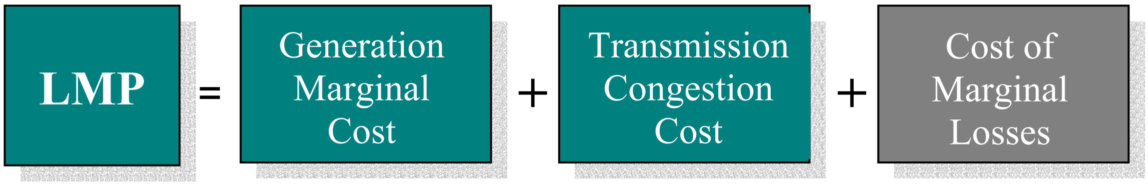


Fig. 3.1 – Components of LMP

node depends on:

- marginal cost of generators,
- operating point of the system, and
- transmission network constraints.

Using nodal pricing, customers buy and sell energy at the actual price of delivering energy to their buses. This pricing system encourages an efficient use of transmission system by assigning prices to users based on the physical way that energy is actually delivered to their buses.

3.1.1 Bidding Procedure

In deregulated power systems, ISO dispatches the generators so that to meet the demand of loads at the minimum cost while maintaining security and service quality of power system. ISO compute LMPs by running optimal power flow. Bidding process for a specified period, e.g. next two hours, is as below.

- Every producer submits the following values to ISO:
  - Minimum and maximum power which can deliver to the network
  - Bid price for selling 1 MW electric power
- Every consumer submits the following values to ISO:
  - Minimum and maximum load demand
  - Load bid for load curtailment in emergency condition (if LMP of a load exceeds its bid then the load is curtailed till its LMP reduces to its bid)
- ISO run the optimal power flow and computes the following values:
  - MW dispatch of each generator
  - MW dispatch of each load
  - LMP of each bus

The mathematical model for computing LMPs is described in the following subsections.

3.1.2 Mathematical Model for Computing Locational Marginal Prices

Consider a deregulated power system and suppose producers and consumers have submitted their bids and other data to ISO for a specific period of times. ISO lists generators based on their bids increasingly. Let's call this list priority list. If there is no constraint in transmission network, the generators are dispatched according to the priority list till sum of generation is made equal to sum of loads and losses. The last dispatched generator, which is not dispatched fully, is named marginal generator. If load of a bus is increased by 1 MW, regardless of the bus location, this 1 MW load will be supplied by the marginal generator. Therefore, according to the definition of LMP, LMPs of all buses are equal to the bid of marginal generator.

If there is constraint in transmission network, the generators are dispatched according to priority list till reach the first constraint. The last dispatched generator can not be dispatched more because of the constraint. Hence, the next generators of the priority list, which do not increase the flow of the congested line, are dispatched respectively till reach the next constraint or sum of generation is made equal to sum of loads and losses. If the generators which have been dispatched after reaching the first constraints decrease the flow of the congested lines, undispatch cheaper generations are dispatched. This process is continued till sum of generation is made equal to sum of loads and losses. In the presence of constraints, there are several marginal generators. If load of a bus is increased by 1 MW, depends on the bus location, this 1 MW load is supplied by the marginal generators which do not violate lime flow limits. Hence, LMP of each bus depends on its location in the network. Therefore, in the presence of transmission constraints LMPs of buses are different. A simple example for LMP is given in appendix C. In practice LMPs are computed using an optimization problem, which is described in the following subsections.

3.1.2.1 Optimal Power Flow

Optimal power flow is modeled by an optimization problem. Objective function is the total cost of operation including cost of running generators and load curtailment cost. Power flow equations, line flow limits, generation limits, and load limits are the constraints of this optimization problem. The objective function and constraints are modeled in (3.1)-(3.5). Consider a power system with N_b buses, N_g generators, N_d loads, and N_l lines. Optimal power flow is modeled as below:

$$\text{Min} \quad \mathrm{J}(\mathbf{P}_G, \mathbf{P}_D) = \mathrm{P}_{Base}\left[\mathbf{C}_G{}^T \mathbf{P}_G + \mathbf{C}_D{}^T (\overset{\max}{\mathbf{P}_D} - \mathbf{P}_D)\right] \tag{3.1}$$

$$\text{s.t.:} \quad \mathbf{B}\delta = \mathbf{P}_G - \mathbf{P}_D - \mathbf{P}_{tie} \tag{3.2}$$

$$-\overset{\max}{\mathbf{P}_\ell} \leq \mathbf{H}\,\delta \leq \overset{\max}{\mathbf{P}_\ell} \tag{3.3}$$

$$\overset{\min}{\mathbf{P}_G} \leq \mathbf{P}_\mathrm{G} \leq \overset{\max}{\mathbf{P}_G} \tag{3.4}$$

$$\overset{\min}{\mathbf{P}_D} \leq \mathbf{P}_\mathrm{D} \leq \overset{\max}{\mathbf{P}_D} \tag{3.5}$$

with:

$\mathrm{J}(\mathbf{P}_G, \mathbf{P}_D)$	1×1	total operation cost in \$/hr
P_{Base}	1×1	base of active power in MW
$\mathbf{C}_G$	$N_b\times1$	vector of generator bids in \$/MWhr (this vector is submitted by producers)
$\mathbf{C}_D$	$N_b\times1$	vector of load bids in \$/MWhr (this vector is submitted by consumers)
$\mathbf{P}_\mathrm{G}$	$N_b\times1$	vector of active power generations in pu (this vector is the output of optimal power flow)
$\mathbf{P}_\mathrm{D}$	$N_b\times1$	vector of active loads in pu (this vector is the output of optimal power flow)
$\mathbf{P}_{tie}$	$N_b\times1$	vector of output power from the study control area to other areas in pu (this vector is determined based on the contracts with neighbouring areas and wheeling transactions)
$\mathbf{B}$	$N_b\times N_b$	linearized Jacobian matrix in pu
$\mathbf{H}$	$N_l\times N_b$	matrix of linearized line flows in pu
δ	$N_b\times1$	vector of voltage angles in radian
$\overset{\min}{\mathbf{P}_G}$, $\overset{\max}{\mathbf{P}_G}$	$N_b\times1$	vectors of minimum and maximum active power generation limits in pu (these vectors are submitted by producers)
$\overset{\min}{\mathbf{P}_D}$, $\overset{\max}{\mathbf{P}_D}$	$N_b\times1$	vectors of minimum and maximum loads limits in pu (these vectors are submitted by consumers)
$\overset{\max}{\mathbf{P}_\ell}$	$N_l\times1$	vector of line limits in pu

The objective function (3.1) represents the total cost of operation. The first term of (3.1) represents the cost that is needed to operate generators. The sum of second and third terms represents the load curtailment cost. The second term of (3.1) is constant and the objective function can be reduced to:

$$\text{Min} \quad \mathrm{J}(\mathbf{P}_G, \mathbf{P}_D) = \mathrm{P}_{Base}\left[\mathbf{C}_G{}^T\, \mathbf{P}_G - \mathbf{C}_D{}^T\, \mathbf{P}_D\right] \tag{3.6}$$

The constraint (3.2) represents the DC power flow equations. The constraint (3.3) represents the line flow limits of the network. The constraint (3.3) and (3.4) represent generation limits and load limits respectively. Power losses are ignored in this method. Linear programming methods like simplex can be used for solving this optimization problem [65].

3.1.2.2 Shadow Prices

Shadow price of a constraint is equal to the change in objective function per unit change in right hand side of the constraint, assuming all other constraints remain unchanged [65]-[66]. A simple example for shadow price is given in appendix D. Rewriting (3.2) in standard form yields:

$$-\mathbf{B}\delta + \mathbf{P}_G - \mathbf{P}_D - \mathbf{P}_{tie} = 0 = \mathbf{b} \tag{3.7}$$

The Lagrangian is formulated as [65]-[66]:

$$\begin{aligned}\mathcal{L}(\mathbf{P}_G, \mathbf{P}_D, \lambda, \psi, \phi, \eta, \zeta, \upsilon, \sigma) = {} & \mathrm{P}_{Base}\left[(\mathbf{C}_G{}^T\, \mathbf{P}_G - \mathbf{C}_D{}^T\, \mathbf{P}_D)\right] - \lambda^T(-\mathbf{B}\delta + \mathbf{P}_G - \mathbf{P}_D - \mathbf{P}_{tie} - \mathbf{b}) \\ & - \psi^T(\mathbf{H}\,\delta - \overset{\max}{\mathbf{P}_\ell} + \mathbf{S}_{l1}^2) - \phi^T(-\mathbf{H}\,\delta - \overset{\max}{\mathbf{P}_\ell} + \mathbf{S}_{l2}^2) \\ & - \eta^T(\mathbf{P}_\mathrm{G} - \overset{\max}{\mathbf{P}_G} + \mathbf{S}_{G1}^2) - \zeta^T(-\mathbf{P}_\mathrm{G} + \overset{\min}{\mathbf{P}_G} + \mathbf{S}_{G2}^2) \\ & - \upsilon^T(\mathbf{P}_\mathrm{D} - \overset{\max}{\mathbf{P}_D} + \mathbf{S}_{D1}^2) - \sigma^T(-\mathbf{P}_\mathrm{D} + \overset{\min}{\mathbf{P}_D} + \mathbf{S}_{D2}^2)\end{aligned} \tag{3.8}$$

with:

$\lambda, \psi, \phi, \eta, \zeta, \upsilon, \sigma$	Lagrange multipliers of the associated constraints
$\mathbf{S}_{l1}, \mathbf{S}_{l2}, \mathbf{S}_{G1}, \mathbf{S}_{G2}, \mathbf{S}_{D1}, \mathbf{S}_{D2}$	slack variables of the associated constraints

Lagrange multipliers, $\mathbf{P}_G$, and $\mathbf{P}_D$ can be calculated by fulfilling Kuhn-Tucker conditions at the optimal solution [65]-[66]. Change in objective function per unit change in $\mathbf{b}$ at the optimal solution ($\mathbf{P}_G^*$, $\mathbf{P}_D^*$, λ^*, ψ^*, ϕ^*, η^*, ζ^*, υ^*, σ^*) is equal to:

$$\left.\frac{\partial \mathrm{J}(\mathbf{P}_G, \mathbf{P}_D)}{\partial \mathbf{b}}\right|_{\text{optimal point}} = \left.\frac{\partial \mathcal{L}(\mathbf{P}_G, \mathbf{P}_D, \lambda, \psi, \phi, \eta, \zeta, \upsilon, \sigma)}{\partial \mathbf{b}}\right|_{\text{optimal point}} = \lambda^* \tag{3.9}$$

Equation (3.9) can be interpreted as below:

If 1 MW load is added to bus i, the total operation cost will increase by $\$\lambda_i$ / MWhr.

Therefore, according to the definition of LMP, LMP of bus i is equal to the shadow price of power flow equation of bus i (see the examples of appendices C and D).

3.2 Probabilistic Locational Marginal Prices

In regulated power systems, probabilistic load flow is used for analyzing electric networks and transmission expansion planning [9]-[11]. In this environment technical criteria, such as the probability of violating line flow limits and bus voltage limits, are used for transmission expansion planning. Technical criteria are computed based on the PDFs of line flow powers and bus voltages.

In deregulated power systems in addition the technical criteria, market based criteria must be used to achieve the objectives of transmission expansion planning in deregulated power systems. In order to define and compute market based criteria, we need to compute the PDFs of variables which show the performance of electric market. These variables should be affected by dynamics of both power system and electric market. This thesis proposes to compute PDFs of LMPs for assessing the performance of electric markets [67]-[72]. In this section a probabilistic tool, which is named "probabilistic optimal power flow" or "probabilistic locational marginal prices", is presented for computing PDFs of LMPs.

3.2.1 Why Probability Density Functions of Locational Marginal Prices?

According to equations (3.1)-(3.5), LMPs will be affected if:

- producers change their bids,
- producers change minimum or maximum of their submitted power,
- consumers change their bids for load curtailment,
- consumers change minimum or maximum of their submitted demands,
- there is transmission constraint in the network,
- transmission facilities (generator, transmission line, load,…) have forced outage,
- input or output power to the study area change due to new contracts with neighboring areas,
- transmitting power through the study area change due to new wheeling transactions, or
- there is market power in the network.

Hence, PDFs of LMPs contain much information about the power system and electric market. Therefore, performance of an electric market can be assessed by analyzing its PDFs of LMPs.

3.2.2 Probabilistic Optimal Power Flow

We use Monte Carlo simulation to compute PDFs of LMPs for a specified scenario. The procedure of computing PDFs of LMPs using Monte Carlo simulation is as below:

- Determining the PDF of each input which has random uncertainty (refer to 3.2.2.1).
- Picking a sample from the PDF of each input (refer to 3.2.2.2).
- Computing LMP of each bus by solving optimal power flow for the picked samples (refer to 3.2.2.3).
- Repeating steps 2 and 3 a great number (number of repetition must be selected so that mean and variance of each output variable converges to a constant value)
- Fitting a PDF to the samples of LMP of each bus (refer to 3.2.2.4).

The above steps are described in detail in the rest of this subsection. Then, the algorithm of computing PDFs of LMPs is presented more precisely in subsection 3.2.3.

3.2.2.1 Determining the Probability Density Functions of Random Inputs

To model the above random uncertainties PDF of each random input variable must be determined. In order to consider the simultaneity of loads and in order to consider the worst conditions, PDFs of random inputs should be determined for the peak load of planning horizon. Some random inputs depend on the other random inputs, for example power of some tie-lines may depend on the power of other tie-lines. In this case, only PDFs of independent random inputs are determined. The values of dependent random inputs are computed based on their relation with the independent random inputs in each iteration of Monte Carlo simulation. To model the random uncertainties of deregulated power systems the following PDFs must be determined for the peak load of planning horizon:

- PDF of each load,
- PDF of bid of each generator,
- PDF of maximum accessible power of each IPP, and
- PDF of power of each tie-line.

PDFs of loads can be determined based on the load prediction and uncertainty analysis [8]. This method can be used for computing PDFs of other random inputs.

To model emergency outage of transmission facilities, unavailability of each transmission facility is determined. A standard uniform PDF is assigned to each transmission facility including each load, generator, and transmission line. In each iteration of Monte Carlo simulation a number is selected from the PDF of each transmission facility randomly. The selected random number, which belongs to [0 1], is compared with the unavailability of the transmission facility. If the selected number is smaller than the associated unavailability, this transmission facility has an emergency outage and must be considered out of circuit in this iteration.

Generation and transmission outages are categorized in:

- planned,
- maintenance, and
- emergency outages.

Planned and maintenance outages must be coordinated with the system operators. Planned and maintenance outages have flexible start dates and predetermined durations. Planned outages last several weeks and maintenance outage last several days. Overhaul, inspection, and testing of boilers and turbines are typical generation planned outages. Planned outages usually occur during the lowest peak load seasons. Maintenance outages are also limited in peak load season. Hence, planned and maintenance outages are ignored in transmission expansion planning. If a power system suffers from the lack of generation, planned and maintenance outages must be considered in transmission expansion planning. To consider planned and maintenance outages in transmission expansion planning, a coordinated plan must be designed for maintenance of all generators in the planning horizon. Suppose the planning horizon is [0 T) and assume N_r is the number of Monte Carlo iterations. If a generator has a planned or maintenance outage in [t_i t_j) then it should be out of circuit in iteration numbers [N_r t_i/T], …, [N_r t_j/T], where [x] denote the biggest integer number smaller than x.

3.2.2.2 Sampling

Sampling from a specified PDF, or generating random numbers based on a specified PDF, should be done so that the set of picked samples is the best estimation for the associated PDF. Generally congruential methods are used for generating random numbers with uniform distribution [73]. Inverse transform method, composition method, and acceptance-rejection method are used for generating random numbers with non-uniform distributions [73]. Sampling methods are out of scope of our discussion in this dissertation.

3.2.2.3 Solving the Optimal Power Flow

In each iteration of Monte Carlo simulation, configuration of the network is determined by sampling from the standard uniform PDFs of transmission facilities. Operating point of the system is determined by sampling from the PDFs of random inputs. Now, the linear optimization problem (3.1)-(3.5) is solved for the specified network configuration and operating point. The outputs of optimal power flow, including generating power of each generator, consuming power of each load, power flow of each line, and LMP of each bus are saved. We use primal-dual simplex method [65] for solving optimal power flow. This optimization problem must be solved at each iteration of Monte Carlo simulation after sampling form the PDFs of random inputs.

3.2.2.4 Estimating the Probability Density Functions of Output Variables

After solving the optimal power flow for enough samples (operating points), we have enough samples for each output variable. In this dissertation, PDF of each output variable is estimated by the normalized histogram of its samples.

It must be noticed that normalized histogram is not a suitable estimation of PDF. In practice a PDF must be fitted to observed samples. In order to find a suitable PDF to mach the observed samples, different theoretical PDFs (e.g. Gaussian, Student, Fisher, Chi-square, Beta, exponential, …) are fitted to the observed samples and the best on is selected using the goodness fit tests (e.g. Kolmogorov-Smirnov and Chi-Square).

3.2.3 Algorithm of Computing the Probability Density Functions of Locational Marginal Prices

The algorithm of computing PDFs of LMPs for a given scenario is as below:

1. Read input data including:
    1.1. network configuration and its parameters
    1.2. unavailability of each transmission facility (transmission lines, generators, and loads)
    1.3. PDF of each independent random input for the peak load of planning horizon including:
        1.3.1. PDF of load of each consumer
        1.3.2. PDF of bid of each generating unit

1.3.3. PDF of maximum accessible power of each IPP

1.3.4. PDF of power of each tie-line

1.4. dependence relationship of each dependent random input versus independent random inputs

1.5. constraints of transmission lines, generators and loads

1.6. planned and maintenance outage program of generators in planning horizon

1.7. number of repetition of Monte Carlo simulation (N_r)

2. Assign a standard uniform PDF to each transmission facility (transmission lines, generators, and loads).
3. Check the planed and maintenance outage program, if a generator has a planned or maintenance outage in this repetition set it to “off”.
4. Pick a number from the standard uniform PDF of each transmission facility randomly and compare it with its associated unavailability. If the number is smaller than its unavailability this transmission facility has a forced outage and set it to “off” else it is “on”.
5. Pick a number from the PDF of each independent random variable and compute the values of dependent random inputs.
6. Solve the optimal power flow, optimization problem (3.1)-(3.5), for the network configuration of step 4 and operating point of step 5 and save the outputs.
7. Repeat steps 3, 4, 5 and 6 N_r times.
8. Fit a PDF to the samples of each output.

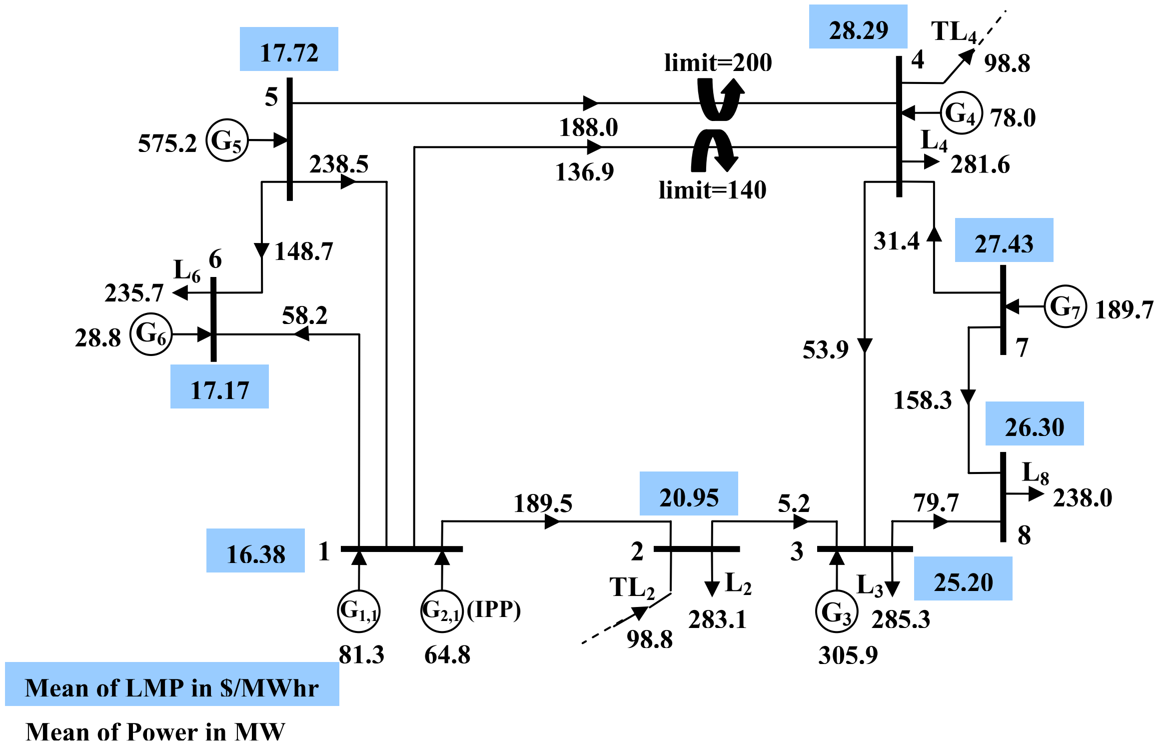


Fig. 3.3 - Test system: eight bus network

3.3 Case Study

The presented approach is applied to the eight-bus network shown in figure 3.3. Data of generation, demand, and power of tie-lines for the peak load of planning horizon are given in tables 3.1, 3.2, and 3.3. Parameters of transmission lines are given in table 3.4. As show tables 3.1-3.3, a normal (Gaussian) PDF is assigned to the bid of each generator, power of each IPP,

Table 3.1 - Generation data of the 8-bus network

Gen. No.	Name	Bus No.	Type	Min	Max (MW)	Bid ($/MWhr)	Unavailability
1	$G_{1,1}$	1	Gen	0	110	N~(14, 2.5)	0.02
2	$G_{2,1}$	1	IPP	0	N~(100,20)	N~(15, 1.8)	0.02
3	G_3	3	Gen	0	520	N~(25, 1.5)	0.02
4	G_4	4	Gen	0	250	N~(30, 2)	0.02
5	G_5	5	Gen	0	600	N~(10, 3)	0.02
6	G_6	6	Gen	0	400	N~(20, 2.1)	0.02
7	G_7	7	Gen	0	200	N~(20, 1.5)	0.02

Table 3.2 - Loads data of the 8-bus network

Load No.	Name	Bus No.	Load (MW)	Bid ($/MWhr)	Unavailability
1	L_2	2	N~(300, 10)	30	0.05
2	L_3	3	N~(300, 12)	32	0.05
3	L_4	4	N~(300, 15)	35	0.05
4	L_6	6	N~(250, 25)	28	0.05
5	L_8	8	N~(250, 25)	35	0.05

Table 3.3 - Tie-lines data of the 8-bus network

Tie-line No.	Name	Bus No.	Power (MW)	Unavailability
1	TL_2	2	N~(100, 10)	0.01
2	TL_4	4	dependent to tie-line TL_2	0.01

Table 3.4 - Parameters of transmission lines of the 8-bus network

Line No.	From Bus No.	To Bus No.	Reactance (pu)	Limit (MW)	Unavailability
1	1	2	0.03	280	0.01
2	1	4	0.03	140	0.01
3	1	5	0.0065	380	0.01
4	2	3	0.01	120	0.01
5	3	4	0.03	230	0.01
6	4	5	0.03	200	0.01
7	5	6	0.02	300	0.01
8	6	1	0.025	250	0.01
9	7	4	0.015	250	0.01
10	7	8	0.022	340	0.01
11	8	3	0.018	240	0.01

* S_{base} = 1000 MVA, V_{base} = 345 KV

power of each tie-line, and load of each consumer. Generator $G_{2,1}$ which is located in bus 1, is an IPP. Due to a wheeling transaction, power transmits through the network via tie-lines TL_2 and TL_4. PDFs of LMPs are computed by picking 2000 samples from the PDFs of inputs. Figure 3.4 shows the PDFs of LMPs for buses 1-8. Mean of generation power, mean of load, mean of power of lines, and mean of LMPs for the peak load of planning horizon are shown in figure 3.3. This figure shows that mean of power of line 2 (line between buses 1 and 4) and line 6 (line between buses 4 and 5) are close to their limits. This means lines 2 and 6 are congested often in the peak load of planning horizon.

LMPs of buses 1 and 2 in different iteration of Monte Carlo simulation are shown in figure 3.5. Figures 3.4.(b) and 3.5.(b) show that LMP of bus 2 is clipped at $30/MWhr. This phenomenon is occurred because of the load curtailment at load bid i.e. $30/MWhr. If LMP of bus 2 exceeds $30/MWhr, load of this bus is curtailed till its LMP reduces to $30/MWhr. In fact each load can be modelled with a fix load which is curtailed never and an imaginary generator with the bid of load. This imaginary generator is dispatched before dispatching more expensive generators. The value of curtailment of this load is equal to the dispatched power of the imaginary generator (see example of appendix C). Figure 3.4 shows that LMPs of buses 3, 4, 6, and 8 are clipped at 32, 35, 28, and $35/MWhr respectively.

The tie-line TL_2 behaves as a generator with zero bid and is dispatched fully always. The tie-line TL_4 behaves as a load with infinity bid and is curtailed never. In operating points which the input power from tie-line TL_2 can not transmit through the network due to transmission

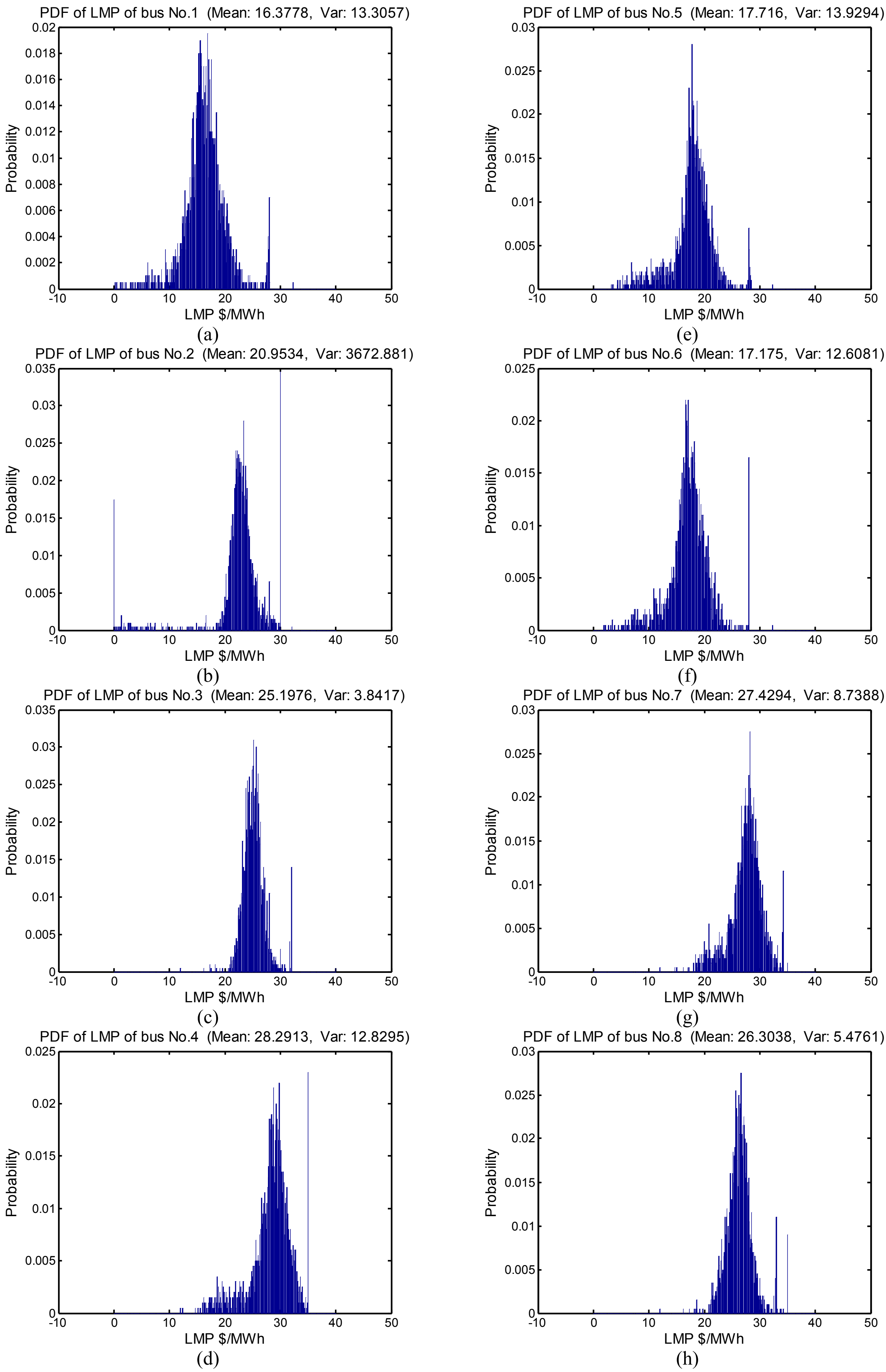
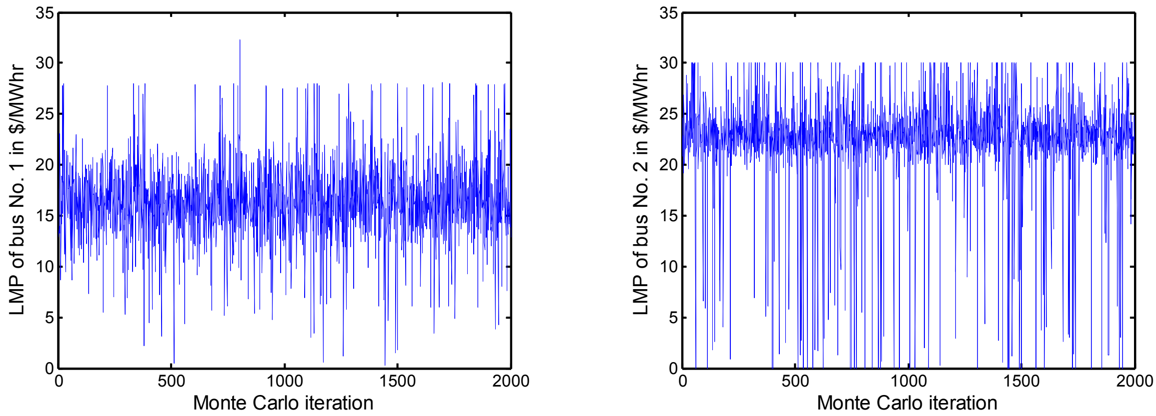


Fig. 3.4 – PDFs of LMPs for the eight bus system



(a) (b)

Fig. 3.5- LMPs of buses 1 and 2 in different iteration of Monte Carlo simulation

congestion, input power of the tie-line TL_2 which behaves as a zero bid generator prevents from dispatching cheap generation near bus 2. This is why the LMP of bus 2 is zero in some operating points (see figures 3.4.(b) and 3.5.(b)). If there is transmission congestion between buses 2 and 4, the output power of tie-line TL_4 is provided by the generators which are located near bus 4. These generators have high bids. Therefore, this wheeling transaction causes expensive generation dispatch instead of cheap generation. This example shows that wheeling transactions affect the LMPs of control areas that transmit through them.

In above example the wheeling power is in the direction of network congestion and increase the intensity of congestion. Now suppose the direction of wheeling changes. Figure 3.6 shows mean of generation power, mean of load, mean of power of lines, and mean of LMPs for wheeling from bus 4 to bus 2. Comparison of figure 3.6 and 3.3 shows if direction of wheeling power changes, the wheeling power decrease the congestion and release transmission capacity. PDFs of power of lines 2 and 6 are shown in figure 3.7. Comparing figures 3.7.a and 3.7.b shows that if direction of wheeling power changes, the probability of congesting line 2 decreases from 0.875 to 0.194. The probability of congesting line 6 decreases from 0.128 to 0.091. This means we can postpone transmission expansion by making wheeling transactions in proper direction. In some cases it may be beneficial to buy expensive power from some control areas and sell it to other control areas in cheaper price to release transmission capacity and postpone transmission expansion. In general a wheeling transaction may congest some lines and release the capacity of some other transmission lines.

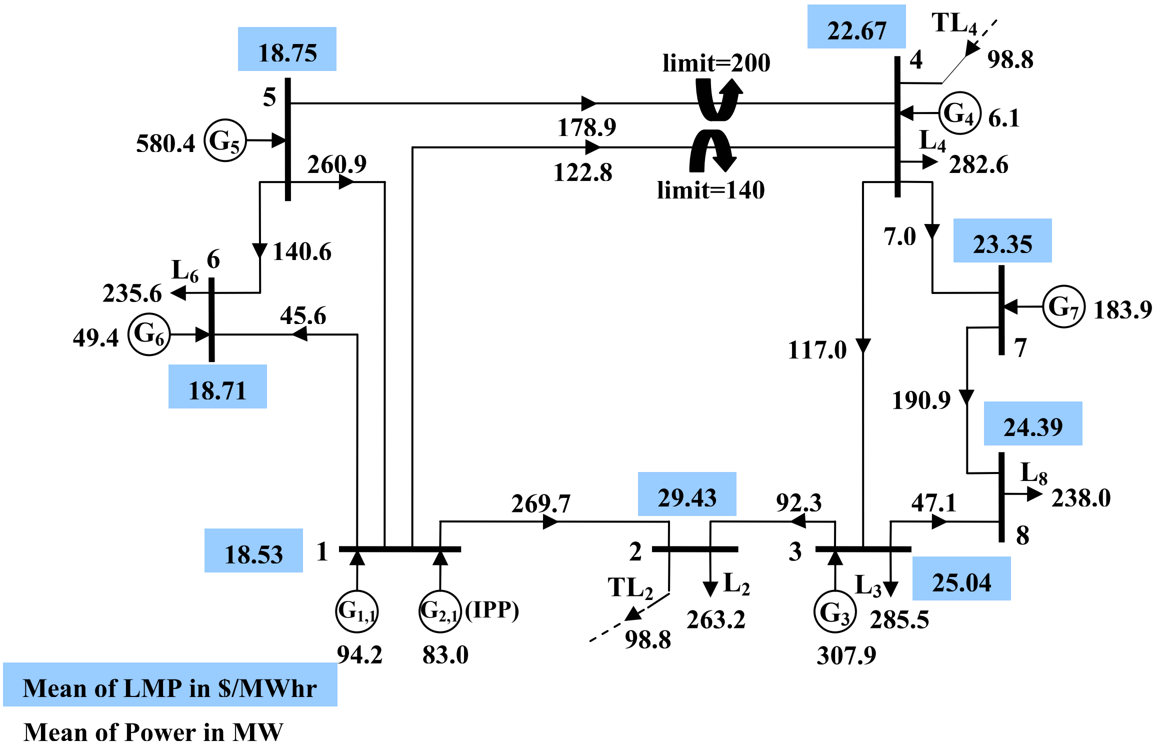
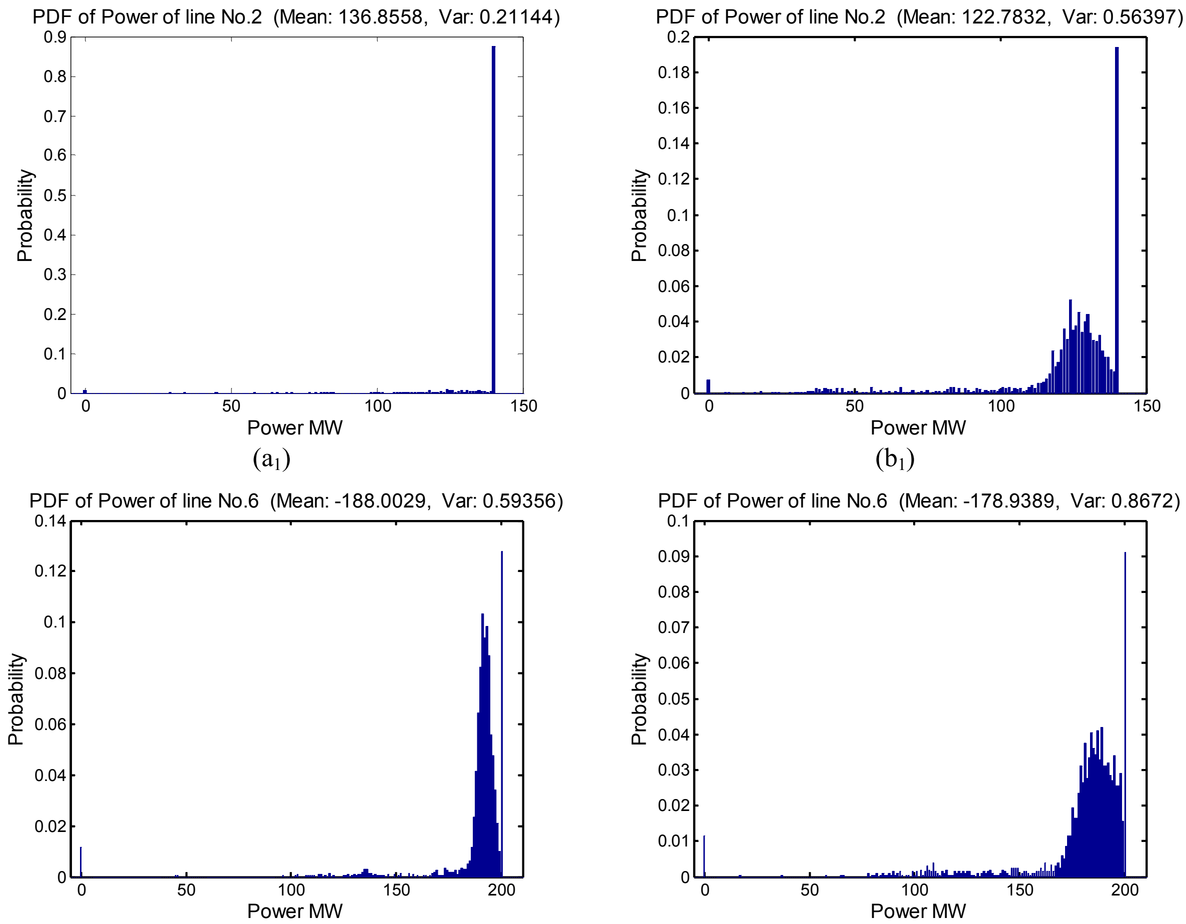


Fig. 3.6 - Test system: eight bus network



(a_1) (b_1)

(a_2) (b_2)

a) Power wheels from bus 2 to bus 4 b) Power wheels from bus 4 to bus 2

Fig. 3.7 – PDFs of power of lines 2 and

4 Market Based Criteria

The main objective of transmission expansion planning in deregulated power systems is to provide a non-discriminatory competitive environment for all stakeholders, while maintaining power system reliability. To achieve this objective, it is needed to define some criteria to measure how competitive an electric market is and how much a specific expansion plan improves the competition. In this chapter market based criteria are presented for transmission expansion planning in deregulated power systems [67]-[68].

This chapter is organized as follows. Requirements of competitive markets are discussed in section 4.1. Market based criteria are presented in section 4.2. In section 4.3 market based criteria are expanded to consider transmission expansion costs. The presented criteria are computed for the 8-bus network in section 4.4.

4.1 Requirements of Competitive Markets

In a perfect competitive market, which consists of infinity number of producers and consumers, the price is determined by interaction of all producers and consumers. In this market each customer produces or consumes only a small portion of the market production. Therefore, a producer or a consumer can not affect the price alone. Hence, in competitive markets producers and consumers are price taker not price maker. In a competitive market there is no discrimination among producers or consumers i.e. all producers and consumers sell and buy at the same price. Moreover, in a competitive market there is no restriction for consumers to buy from any producer. To have a competitive electric market, the above conditions must be satisfied. On the other word, to have a competitive electric market all power producers and consumers must sell and buy electric energy at the same price and the power transfer restrictions must be alleviated. This means LMPs must be made equal at all buses and transmission congestion must be alleviated. Equalizing LMPs provides a non-discriminatory market and alleviating congestion eliminates power transmission constraints.

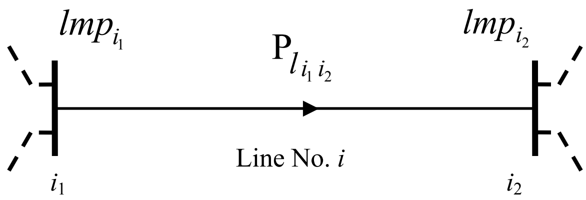


Fig. 4.1 – Line No. i of a network

4.2 Market Based Criteria

In this section two probabilistic criteria, average congestion cost and standard deviation of mean of LMP, are proposed to measure how much a specific plan facilitates competition among customers. Average congestion cost shows how intensive transmission constraints are and consequently shows how competitive electric market is. Standard deviation of mean of LMP shows how mean of LMP spreads throughout the network. Therefore, it shows how discriminative and consequently how competitive electric market is.

4.2.1 Transmission Congestion

A line is congested if its power has reached to its limit. Transmitting more power through this line is not allowed. In other words, a line is congested if its associated constraint in (3.3) is active. Under transmission congestion next MW of some loads can not be supplied by the cheapest undispatched generation. The next MW of these loads, depending on their places in the network, is supplied by other more expensive generations. Hence, under congestion buses have different LMPs.

Congestion cost of a line is defined as the opportunity cost of transmitting power through it. Consider figure 4.1, line i of a network is depicted in this figure. The end buses of this line numerated with i_1 and i_2. $P_{l_{i_1 i_2}}$ MW electric power transmits from bus i_1 to bus i_2 through this line. LMPs of buses i_1 and i_2 are lmp_{i_1} and lmp_{i_2} in \$/MWhr. Buying 1 MW electric power from bus i_1 costs lmp_{i_1} \$/hr and buying 1 MW power from bus i_2 costs lmp_{i_2} \$/hr. Therefore, the opportunity cost of transmitting 1 MW electric power from bus i_1 to bus i_2 is equal to $(lmp_{i_2} - lmp_{i_1})$ \$/hr. Thus, congestion cost of line i or the opportunity cost of transmitting $P_{l_{i_1 i_2}}$ MW electric power from bus i_1 to bus i_2 through line i is equal to:

$$cc_i = (lmp_{i_2} - lmp_{i_1})P_{l_{i_1 i_2}} \quad i=1, 2,\ldots, N_l \tag{4.1}$$

with

cc_i congestion cost of line i in \$/hr

N_l number of network lines

Total congestion cost of the network or the opportunity cost of transmitting power though the network is equal to:

$$tcc = \sum_{i=1}^{N_l} (lmp_{i_2} - lmp_{i_1})P_{l_{i_1 i_2}} \tag{4.2}$$

with:

tcc total congestion cost of the network in \$/hr

It can be proved that the total congestion cost of the network is equal to the sum of payments by loads minus sum of receives by generators, i.e.:

$$tcc = \sum_{i=1}^{N_b} P_{d_i} lmp_i - \sum_{i=1}^{N_b} P_{g_i} lmp_i \tag{4.3}$$

with

P_{d_i} load at bus i in MW

P_{g_i} generation power at bus i in MW

N_b number of network buses

If there is no congestion in the network, the next MW of each load is supplied by the cheapest undispatched generation (marginal generator) and then LMPs of all buses are equal. In this case, according to (4.2) total congestion cost of the network is zero.

Consider a network and suppose some expansion plans were suggested for transmission expansion. Each expansion plan is added to the network separately. The plan which decreases more transmission constraint; causes more undispatched cheap generation are dispatched. Hence, this plan causes less LMP differences among buses and consequently less congestion cost. Therefore, congestion cost is a proper criterion for measuring price discrimination (LMP differences among buses) and transmission constraints. Consequently, congestion cost is a proper criterion for measuring the competitiveness degree of electric markets. In the other word, change in congestion cost after addition of an expansion plan is a proper criterion to measure how much the plan facilitates the competition. To consider random uncertainties average of total congestion cost is suggested for measuring the competitiveness degree of electric markets.

Now consider a network with N_b buses and N_l lines. Suppose some expansion plans were suggested for transmission expansion. Each expansion plan is added to the network separately. Monte Carlo simulation is used for computing PDFs of LMPs using N_r samples. Congestion cost of line i after addition of plan k in the jth iteration of Monte Carlo simulation is equal to:

$$cc_{i,j}^{k} = (lmp_{i_2,j}^{k} - lmp_{i_1,j}^{k})\ \mathrm{P}_{l_{i_1 i_2},j}^{k} \tag{4.4}$$

with:

$cc_{i,j}^{k}$	congestion cost of line i after addition of plan k in the jth iteration of Monte Carlo simulation in \$/hr
$lmp_{i_1,j}^{k}$	LMP of bus i_1 after adding plan k in the jth iteration of Monte Carlo simulation in \$/MWhr
$\mathrm{P}_{l_{i_1 i_2},j}^{k}$	power of line i which flows from bus i_1 to bus i_2 after adding plan k in the jth iteration of Monte Carlo simulation in MW

Note that it is indifferent which end of line i is numerated i_1 or i_2. If numeration changes, the sign of $(lmp_{i_2,j}^{k} - lmp_{i_1,j}^{k})$ and $\mathrm{P}_{l_{i_1 i_2},j}^{k}$ change and consequently $cc_{i,j}^{k}$ remains unchanged. Total congestion cost of the network is given by:

$$tcc_{j}^{k} = \sum_{i=1}^{N_l} cc_{i,j}^{k} \tag{4.5}$$

with:

tcc_{j}^{k}	total congestion cost of the network after adding plan k in the jth iteration of Monte Carlo simulation in \$/hr

Average of the total network congestion cost after addition of plan k is equal to:

$$\mu_{tcc}^{k} = \frac{1}{N_r}\sum_{j=1}^{N_r} tcc_{j}^{k} \tag{4.6}$$

with:

μ_{tcc}^{k}	average of total congestion cost of the network in the presence of plan k in \$/hr

In the rest of this thesis “average congestion cost” is used instead of “average of total congestion cost of the network”.

4.2.2 Flatness of Price Profile

Again consider a network with N_b buses and N_l lines. Suppose some plans were suggested for transmission expansion. Assume PDFs of LMPs were computed for each plan using N_r samples. The mean of LMP of bus i over N_r samples in the presence of plan k is given by:

$$\mu_{lmp_i}^{k} = \frac{1}{N_r}\sum_{j=1}^{N_r} lmp_{i,j}^{k} \qquad i=1, 2,\ldots, N_b \tag{4.7}$$

with:

$\mu_{lmp_i}^{k}$ mean of LMP of bus i in the presence of plan k in \$/MWhr

Consider a Cartesian coordination for the network and suppose x_i , and y_i are Cartesian coordinates of bus i.

***Definition*:**

The surface which is fitted to the points (x_i, y_i, $\mu_{lmp_i}^{k}$) for i=1, 2,…, N_b using linear interpolation method is named piece profile of the network in the presence of plan k.

Price profile always passes through all data points. The z magnitude of other points is determined by linear interpolation. Consider the example of section 3.3. The 8-bus network of section 3.3 with the associated PDFs of LMPs is shown in figure 4.2. Figure 4.3 shows the 8-bus network on the xy-plane of Cartesian coordination. The mean of LMP of each bus has been specified by a bar over it. In figure 4.4 a surface has been fitted to the points (x_i, y_i, $\mu_{lmp_i}^{0}$) for i=1, 2,…, 8 using linear interpolation. Where $\mu_{lmp_i}^{0}$ is the mean of LMP of bus i for the existing network (before adding any expansion plan to the network). This surface is named price profile of the existing network. Price profile is defined to make the presented criteria more sensible. The points of price profile surface, which are not located over a bus, are not meaningful.

In nodal pricing all customers purchase and sell electric energy at the LMP of their buses. In order to provide an environment that all customers purchase and sell energy at the same price, nodal prices must be made equal. On the other word, price profile must be made flat. As the price profile becomes flatter, differences among the mean of LMP of different buses decrease.

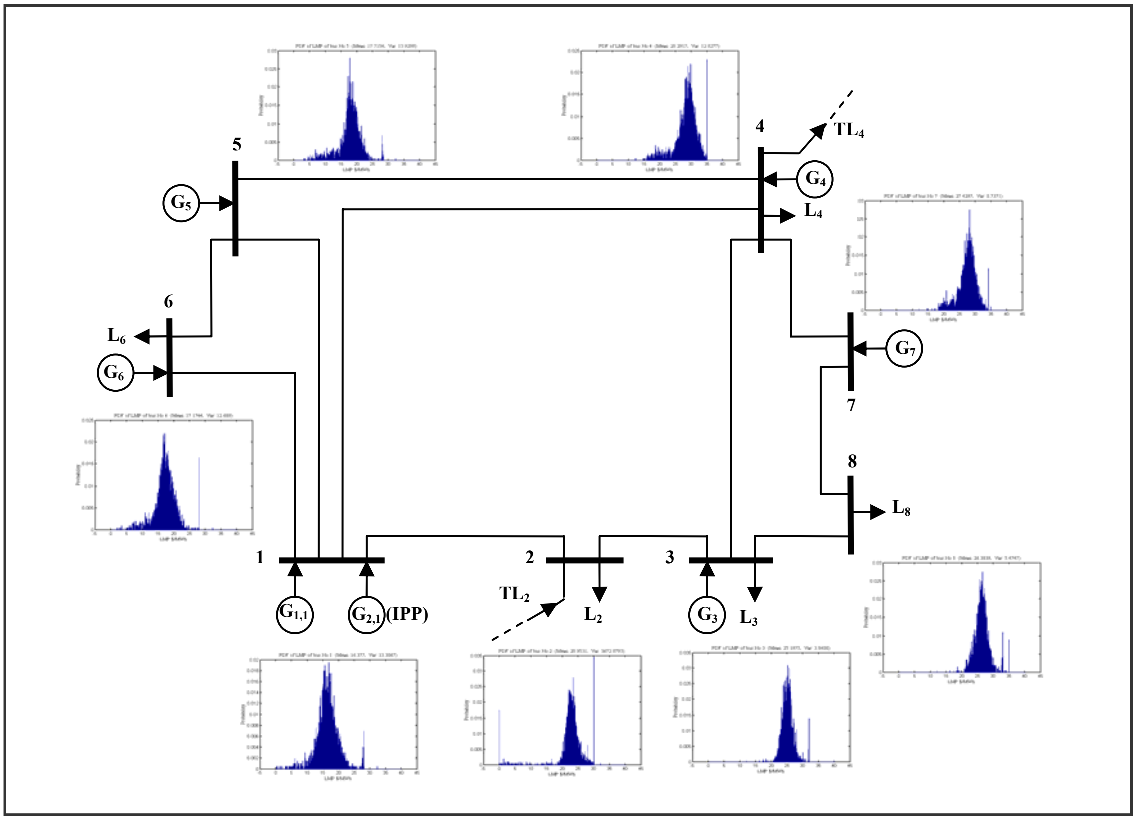


Fig. 4.2 – The 8-bus network with its PDFs of LMPs

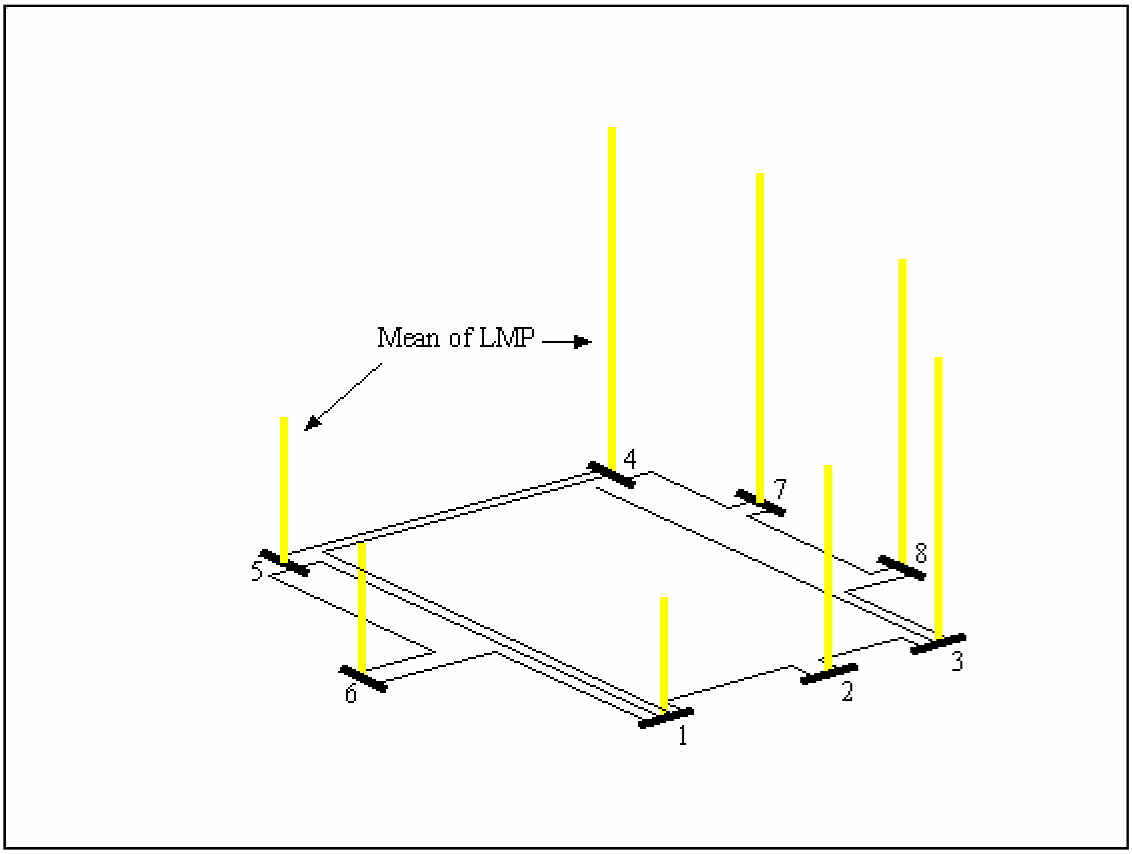


Fig. 4.3 – The 8-bus network with the mean of LMP of each bus over it

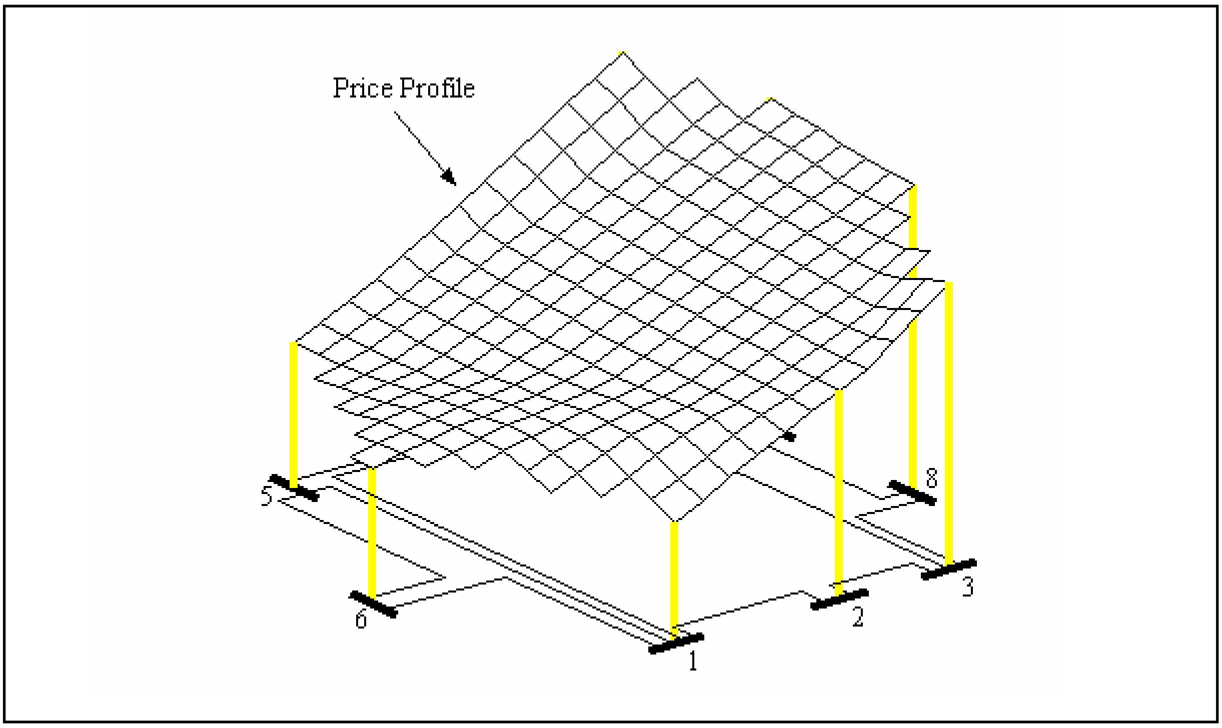


Fig. 4.4 – Price profile of the 8-bus network

Therefore, customer buy and sell energy at less discriminative prices and consequently competition is encouraged. As the price profile deviate from the flatness, differences among the mean of LMP of different buses increase, customers buy and sell at more discriminative prices, and consequently competition is discouraged. Therefore, the flatness of price profile is a proper criterion for measuring the competitiveness degree of electric markets.

4.2.2.1 Standard Deviation of Mean of Locational Marginal Price

Consider figure 4.3, mean of LMP of each bus is specified with a bar over it. Standard deviation of mean of LMP in the presence of plan k, where mean is taken over N_r samples and standard deviation is taken over N_b buses, is given by:

$$\sigma^{k}_{\mu_{lmp}} = \sqrt{\frac{1}{N_b - 1}\sum_{i=1}^{N_b}(\mu^{k}_{lmp_i} - \mu^{k}_{lmp})^2} \tag{4.8}$$

with:

$\sigma^{k}_{\mu_{lmp}}$ standard deviation of mean of LMP in the presence of plan k in \$/MWhr

$\mu^{k}_{lmp_i}$ mean of LMP of bus i over N_r samples in the presence of plan k in \$/MWhr

μ^{k}_{lmp} mean of $\mu^{k}_{lmp_i}$ over N_b buses in \$/MWhr (average LMP of the network)

μ_{lmp}^{k} is equal to:

$$\mu_{lmp}^{k} = \frac{1}{N_b} \sum_{i=1}^{N_b} \mu_{lmp_i}^{k} \tag{4.9}$$

Standard deviation of mean of LMP in the presence of plan *k* ($\sigma_{\mu_{lmp}}^{k}$) indicates how spread out the mean of LMP of different buses ($\mu_{lmp_i}^{k}$ for i=1, 2,…, N_b) are from the average LMP of the network (μ_{lmp}^{k}). As the standard deviation of mean of LMP decreases, differences among the mean of LMP of different buses decrease and the price profile become flatter. Flatter price profile indicates less price discrimination. According to (4.2) as flatness of price profile increases, congestion cost decreases. Therefore, as the standard deviation of mean of LMP decreases, both transmission constraints and price discrimination decrease and hence competition is encouraged. In the same way as the standard deviation of mean of LMP increases, competition is discouraged. Therefore, standard deviation of mean of LMP is a proper criterion for measuring the competitiveness degree of electric markets.

Since the budget of transmission expansion is limited, it is logical to provide a competitive field for more participants or for more power with a given budget. Hence, weighted standard deviation of mean of LMP is proposed for ranking the transmission plans:

$$\sigma_{\mu_{lmp},w}^{k} = \sqrt{\frac{1}{N_b - 1} \sum_{i=1}^{N_b} w_i^k (\mu_{lmp_i}^{k} - \mu_{lmp}^{k})^2} \tag{4.10}$$

with:

$\sigma_{\mu_{lmp},w}^{k}$ weighted standard deviation of mean of LMP with the weight w in the presence of plan *k* in \$/MWhr

w_i^k weight of bus *i* after adding plan *k*

Generation power, load, and sum of generation power and load are suggested to weight each bus.

4.2.2.2 Weighting with Mean of Generation Power

The mean of generation power at bus *i* after adding plan *k* in the peak load of planning horizon is given by:

$$\mu_{P_{g_i}}^k = \frac{1}{N_r}\sum_{j=1}^{N_r} P_{g\,i,j}^k \qquad \text{for } i=1, 2,\ldots, N_b \tag{4.11}$$

with:

$P_{g\,i,j}^k$ generation power of bus i after addition of plan k in the jth iteration of Monte Carlo simulation in MW

$\mu_{P_{g_i}}^k$ mean of generation power at bus i after adding plan k in MW

If weighted standard deviation of mean of LMP with the weight:

$$w_i^k = \mu_{P_{g_i}}^k \qquad \text{for } i=1, 2,\ldots, N_b \tag{4.12}$$

is used as planning criterion, the plan which minimizes the sum of weighted square errors between mean of LMP of generation buses and average LMP of the network (μ_{lmp}^k) is selected as the final plan. Therefore, this criterion decreases price discrimination among producers and hence encourages competition among them. This criterion assigns greater weight to the buses which have greater generation. Hence, this criterion tries to provide a competitive environment for more generation power. Since this criterion assigns weight zero to the buses that do not have generation, it does not provide a non-discriminatory environment for consumers necessarily.

4.2.2.3 Weighting with Mean of Load

The mean of load of bus i is given by:

$$\mu_{P_{d_i}}^k = \frac{1}{N_r}\sum_{j=1}^{N_r} P_{d\,i,j}^k \qquad \text{for } i=1, 2,\ldots, N_b \tag{4.13}$$

with:

$P_{d\,i,j}^k$ load of bus i after addition of plan k in the jth iteration of Monte Carlo simulation in MW

$\mu_{P_{d_i}}^k$ mean of load at bus i after adding plan k in MW

If weighted standard deviation of mean of LMP with the weight:

$$w_i^k = \mu_{P_{d_i}}^k \qquad \text{for } i=1, 2,\ldots, N_b \tag{4.14}$$

is used as planning criterion, the plan which minimizes the sum of weighted square errors between mean of LMP of load buses and average LMP of the network is selected as the final plan. Therefore, this criterion decreases price discrimination among load buses and hence provides a non-discriminatory environment for consumers. This criterion assigns greater weight to the buses which have greater load. Hence, this criterion tries to provide a non-discriminatory environment for more loads. Since this criterion assigns weight zero to the buses that do not have load, it does not encourage competition among producers necessarily.

4.2.2.4 Weighting with Sum of Mean of Generation Power and Load

The mean of sum of generation power and load at bus i is given by:

$$\mu^k_{(P_{g_i}+P_{d_i})} = \frac{1}{N_r}\sum_{j=1}^{N_r}(P^k_{g\,i,j} + P^k_{d\,i,j}) \qquad \text{for } i=1, 2,\ldots, N_b \tag{4.15}$$

with:

$\mu^k_{(P_{g_i}+P_{d_i})}$ mean of sum of generation power and load at bus i after adding plan k in MW

If the weighted standard deviation of mean of LMP with the weight:

$$w_i^k = \mu^k_{(P_{g_i}+P_{d_i})} \qquad \text{for } i=1, 2,\ldots, N_b \tag{4.16}$$

is used as planning criterion, the plan which minimizes the sum of weighted square errors between mean of LMP of each bus and average LMP of the network is selected as the final plan. Therefore, this criterion decreases price discrimination among all customers and hence provides a non-discriminatory competitive environment for them. This criterion assigns greater weight to the buses which have greater sum of load and generation. Hence, this criterion tries to provide a competitive environment for more loads and generations.

4.2.3 Load Payment

Form the viewpoint of power consumers total payment for buying power, i.e. total generation receives plus total congestion cost, is important. Hence, average of total load payment can be used as a criterion for transmission expansion planning. Average of total load payment during the peak load of planning horizon after adding plan k is equal to:

$$\mu^k_{tlp} = \frac{1}{N_r}\sum_{j=1}^{N_r}\sum_{i=1}^{N_b} P^k_{d\,i,j}\, lmp^k_{i,j} \tag{4.17}$$

with:

μ_{tlp}^{k} average of total load payment during the peak load of planning horizon after adding plan k in \$/hr

This criterion, however, does not consider competition among customers. In the rest of this thesis "average load payment" is used instead of "average of total load payment".

4.3 Transmission Expansion Costs

Justification of costs is very important in competitive environments. Therefore expansion planning criteria must take into account transmission expansion costs. Transmission expansion cost is divided into investment and operation costs. In this section, the presented criteria are developed in order to consider transmission expansion costs.

When a new plan is added to the network operation cost changes. Thus, transmission expansion planning criteria must consider operation costs. Average cost of running generators during the peak load of planning horizon after adding plan k is equal to:

$$\mu_{rgc}^{k} = \frac{1}{N_r} \sum_{j=1}^{N_r} \sum_{i=1}^{N_g} P_{g\,i,j}^{k} \; C_{g\,i,j} \tag{4.18}$$

with:

μ_{rgc}^{k} average cost of running generators after adding plan k in \$/hr

$C_{g\,i,j}$ bid of generator i in the jth iteration of Monte Carlo simulation in \$/MWhr

N_g number of generators

Average load curtailment cost during the peak load of planning horizon after adding plan k is equal to:

$$\mu_{lcc}^{k} = \frac{1}{N_r} \sum_{j=1}^{N_r} \sum_{i=1}^{N_d} P_{c\,i,j}^{k} \; C_{d\,i,j} \tag{4.19}$$

with:

μ_{lcc}^{k} average load curtailment cost after adding plan k in \$/hr

$P_{c\,i,j}^{k}$ amount of curtailment of load i after adding the plan k in the jth iteration of Monte Carlo simulation in MW or $(P_{d\,i,j}^{\max} - P_{d\,i,j}^{k})$

$C_{d_{i,j}}$	bid of load *i* in the *j*th iteration of Monte Carlo simulation in \$/MWhr
N_d	number of loads

When we try to reduce average congestion cost or weighted standard deviation of mean of LMP by transmission expansion planning, network constraint for dispatching undispatched cheap generation decreases and some curtailed loads can be supplied. Consequently, cost of running generators and load curtailment cost decrease. Therefore, operation cost is considered by the presented criteria indirectly. Load curtailment cost is a criterion for measuring reliability. Therefore, reliability is also considered by the presented criteria. On the other word, in the presence of more reliable plans, emergency outage of transmission facilities provide less transmission constraint and consequently less congestion cost and less weighted standard deviation of mean of LMP. Therefore, reliability is also taken into account by the presented criteria. Note that emergency outage of transmission facility was modelled is computing LMP (see chapter 3).

Investment cost consists of the cost of corridor, towers, wires, other accessories and construction. Transmission expansion planning must be value based. From the view of value based planning approaches the plan which provides the best criterion value per unit of transmission cost is the optimal plan. In order to have value based criteria for transmission expansion planning the presented criteria must be normalized on transmission costs. Hence, the following normalized criteria are suggested for transmission expansion planning.

- ***Decrease in annual congestion cost divided by annual transmission cost:***

Suppose T_{Peak} is the total peak load time per year. Annual congestion cost of the network after adding plan *k* is given by:

$$ANCC^k = T_{Peak}\ \mu_{tcc}^k \tag{4.20}$$

with:

$ANCC^k$	annual congestion cost of the network after adding plan *k* in \$
T_{Peak}	total peak load time per year in hr

Annual operation cost after adding plan *k* to the network is equal to:

$$ANOC^k = T_{Peak}\ \mu_{rgc}^k \tag{4.21}$$

with:

$ANOC^k$ annual operation cost of the network after adding plan k in \$

Decrease in annual operation cost after adding plan k to the network is equal to:

$$DANOC^k = ANOC^0 - ANOC^k \tag{4.22}$$

with:

$DANOC^k$ decrease in annual operation cost of the network after adding plan k in \$

$ANOC^0$ annual operation cost of the existing network in \$

Decrease in annual congestion cost per unit of annual transmission cost on plan k is given by:

$$F_{ANCC}^k = \frac{ANCC^0 - ANCC^k}{ANIC^k - DANOC^k} \tag{4.23}$$

with:

F_{ANCC}^k decrease in annual congestion cost per unit of annual transmission cost of plan k

$ANIC^k$ annual investment cost of plan k in \$

This criterion shows how much annual congestion cost deceases per unit of transmission cost. On the other word, it shows how much competition is encouraged per unit of transmission cost.

- ***Decrease in weighted standard deviation of mean of LMP divided by annual transmission cost:***

Decrease in weighted standard deviation of mean of LMP per unit of annual transmission cost of plan k is equal to:

$$F_{\sigma_{\mu_{lmp},w}}^k = \frac{\sigma_{\mu_{lmp},w}^0 - \sigma_{\mu_{lmp},w}^k}{ANIC^k - DANOC^k} \tag{4.24}$$

with:

$F_{\sigma_{\mu_{lmp},w}}^k$ decrease in weighted standard deviation of mean of LMP per unit of annual transmission cost of plan k

$\sigma_{\mu_{lmp},w}^k$ weighted standard deviation of mean of LMP with the weight w in the presence of plan k in \$/MWhr

This criterion shows how much the flatness of price profile improves per unit of transmission cost. On the other word, it shows how much competition is encouraged per unit of transmission cost.

- ***Decrease in annual load payments divided by annual transmission cost:***

The annual load payment during the peak load of planning horizon after adding plan k is given by:

$$ANLP^k = T_{Peak}\ \mu_{tlp}^k \tag{4.25}$$

with:

$ANLP^k$ annual load payment during the peak load of planning horizon after adding plan k in \$

Decrease in annual load payment per unit of annual transmission cost of plan k is equal to:

$$F_{ANLP}^k = \frac{ANLP^0 - ANLP^k}{ANIC^k - DANOC^k} \tag{4.26}$$

with:

F_{ANLP}^k decrease in annual load payment per unit of annual transmission cost of plan k

This criterion shows how much annual load payments deceases per unit of transmission cost. However, this criterion does not consider competition among customers.

4.4 Case Study

Consider the 8-bus network of section 3.3, which is redrawn in figure 4.5. Network engineers suggest the following plans for transmission expansion:

Plan 1: installing a line between buses 1 and 4
Plan 2: installing a line between buses 2 and 4
Plan 3: installing a line between buses 5 and 4
Plan 4: installing a line between buses 2 and 3
Plan 5: installing a line between buses 5 and 3

In order to select the plan which encourages competition at the most, each plan is added to the network and market based criteria are computed for each plan. Due to the lack of data about transmission cost of the suggested expansion plans, transmission cost is ignored in this example ($\sigma_{\mu_{lmp}}^k$ is used as planning criterion instead of $F_{\sigma_{\mu_{lmp}}}^k$ and so on).

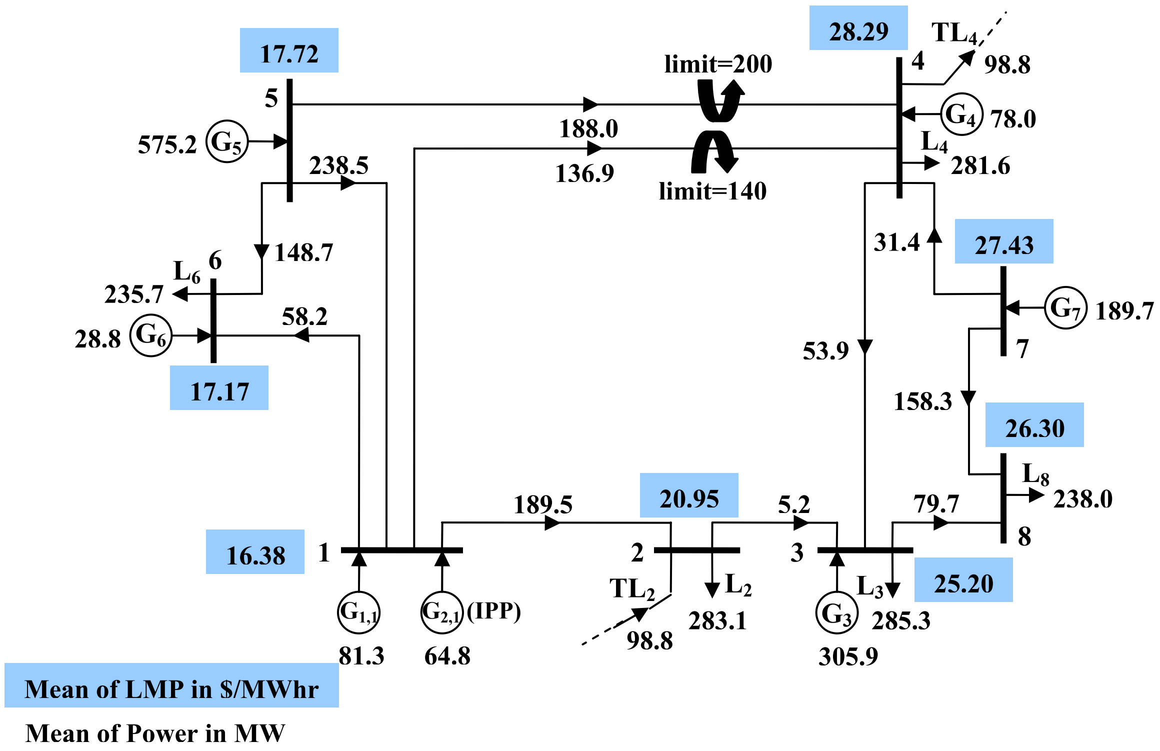


Fig. 4.5 - Test system: eight bus network

Table 4.1 shows the value of planning criteria for suggested expansion plans. Figures 4.6 and 4.7 show the mean of generation power, mean of load, mean of power of lines, and mean of LMPs after adding plans 3 and 5 to the network. Table 4.1 shows that plan 3 has the minimum weighted standard deviation of mean of LMP ($\sigma^k_{\mu_{lmp}}$, $\sigma^k_{\mu_{lmp},w=P_g}$, $\sigma^k_{\mu_{lmp},w=P_d}$, and $\sigma^k_{\mu_{lmp},w=P_g+P_d}$) or the flattest price profile. This means that plan 3 provide a less discriminative environment and hence from the viewpoint of these criteria, plan 3 facilitates competition more than other suggested plans. Figures 4.6 and 4.7 confirm this matter. These figures show that maximum LMP difference after adding plan 3 is $5.52/MWhr and after adding plan 5 is $8.98/MWhr and hence plan 3 provides a less discriminative environment. Comparison of figure 4.5 with figures 4.6 and 4.7 shows that both plan 3 and 5 reduce the power of congested lines 2 (line between buses 1 and 4) and 6 (line between buses 4 and 5). Plan 3 reduce the power of line 2 more than line 6 but plan 5 reduce the power of line 6 more than line 2. Table 4.1 shows that plan 5 has the minimum average congestion cost (μ^k_{tcc}). Hence from the viewpoint of this criterion, plan 5 facilitates competition more than other suggested plans. Table 4.1 shows that plan 3 also has the minimum load payment (μ^k_{tlp}) and

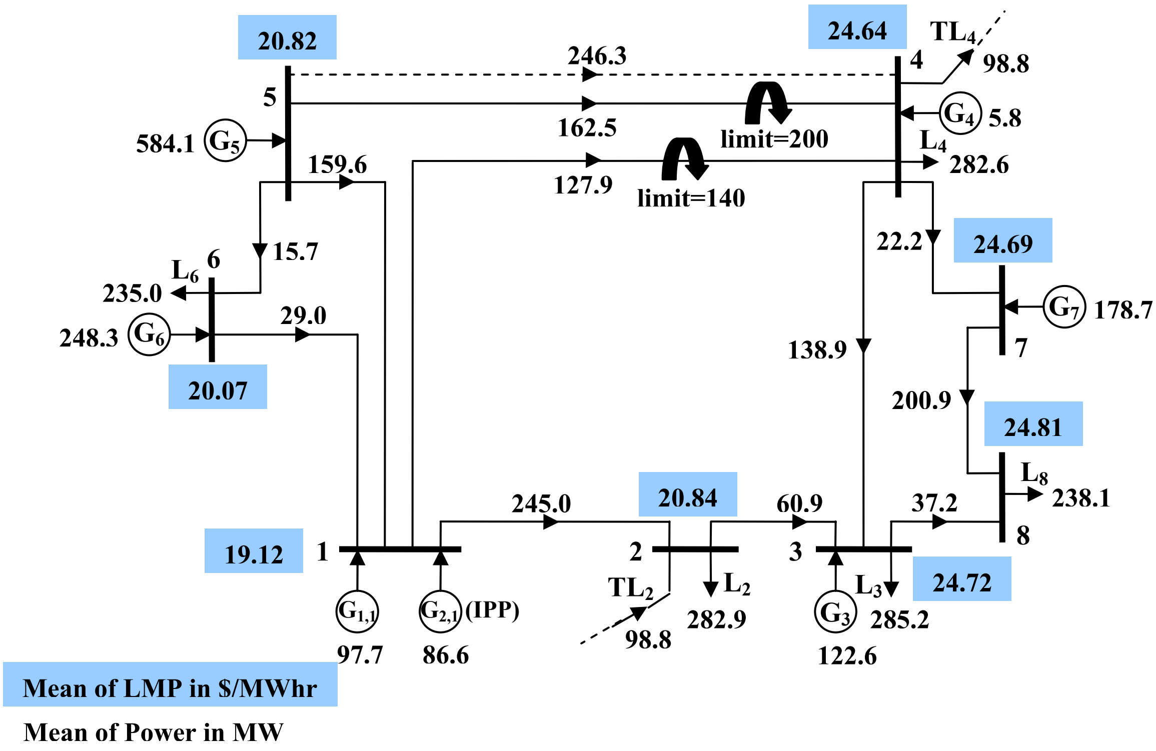


Fig. 4.5 – The eight bus network after adding plan 3

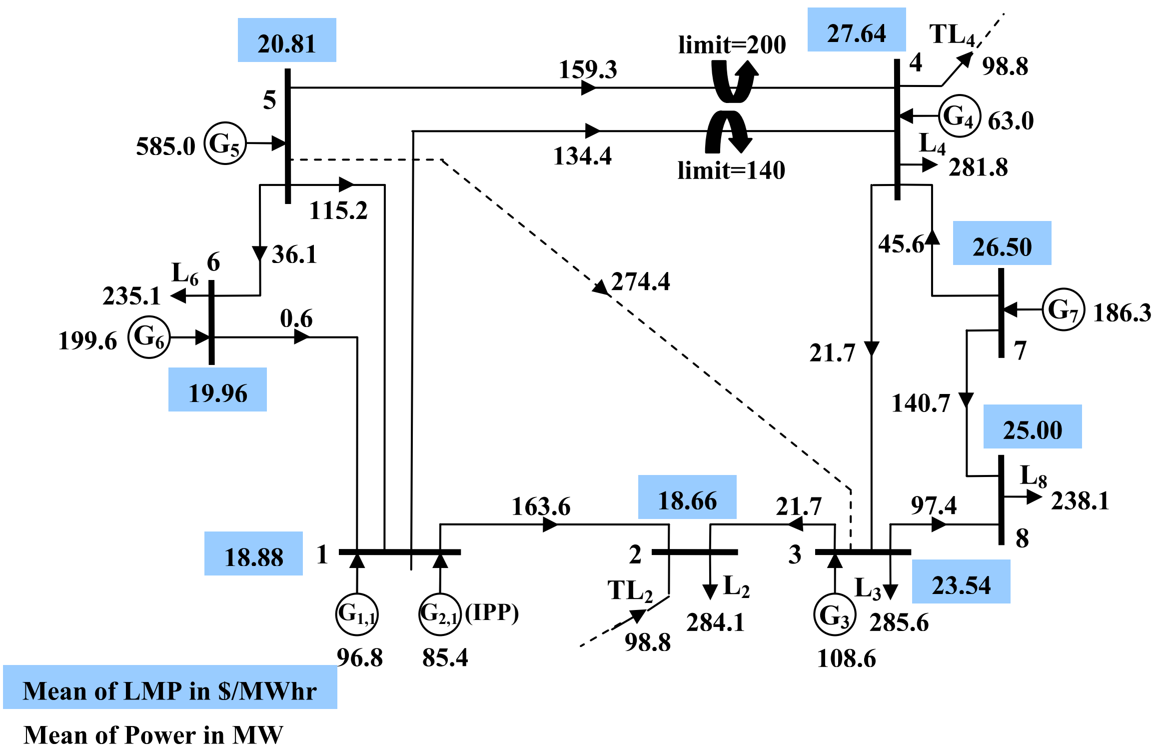


Fig. 4.6 - The eight bus network after adding plan 5

Table 4.1 – Value of the market based criteria for the suggested plans

	Existing Network	Plan 1 (line: 1-4)	Plan 2 (line: 2-4)	Plan 3 (line: 5-4)	Plan 4 (line: 2-3)	Plan 5 (line: 5-3)	Selected Plan (line: ? - ?)
$\sigma^k_{\mu_{lmp}}$	4.9381	2.8802	5.0796	**2.4649**	4.8475	3.5199	3 (5 – 4)
$\sigma^k_{\mu_{lmp},w=P_g}$	2.0248	1.4028	2.1103	**0.9712**	2.0426	1.2166	3 (5 – 4)
$\sigma^k_{\mu_{lmp},w=P_d}$	1.7953	1.0926	1.7824	**0.9406**	1.7105	1.4536	3 (5 – 4)
$\sigma^k_{\mu_{lmp},w=P_g+P_d}$	2.7061	1.7781	2.7623	**1.3521**	2.6642	1.8955	3 (5 – 4)
μ^k_{tcc}	4510	4524	4384	3677	4505	**3509**	5 (5 – 3)
μ^k_{tlp}	32280	31846	31766	**31729**	32604	31741	3 (5 – 4)

** Dimension of $\sigma^k_{\mu_{lmp},w}$ is \$/MWhr, and Dimension of μ^k_{tcc} and μ^k_{tlp} is \$/hr.

hence from the viewpoint of this criterion plan 3 is selected as the final plan. Now the following questions arise:

- Which criterion does provide the best environment for competition? On the other word, less congestion cost leads to more competitive environment or smaller weighted standard deviation of mean of LMP?
- Table 4.1 shows that after installing plan 3 or 5 there is considerable congestion cost and LMP difference. Therefore, to have a perfect competitive market other lines must be added to the network. The question is which criterion leads to a perfect competitive market at minimum cost or at minimum number of expansion plans.
- In this example $\sigma^k_{\mu_{lmp}}$, $\sigma^k_{\mu_{lmp},w=P_g}$, $\sigma^k_{\mu_{lmp},w=P_d}$, $\sigma^k_{\mu_{lmp},w=P_g+P_d}$, and μ^k_{tlp} lead to the same result. Do they lead to the same result always?

Although the above questions do not have absolute answers and their answers depend on the network structure, we try to make their answers more clear with an example after presenting an approach for transmission expansion planning in the next chapter.

5 Market Based Transmission Expansion Planning

In chapter 3 a probabilistic tool for computing PDFs of LMPs was presented. In chapter 4 market based criteria were presented for transmission expansion planning in deregulated power systems. In this chapter a new approach is presented for transmission expansion planning in deregulated power systems using the probabilistic tool which is presented in chapter 3 and the market based criteria which are presented in chapter 4 [68]. This approach takes into account both random and non-random uncertainties and tries to provide a competitive electric market for customers.

This chapter is organized as follows. The presented model is overviewed in section 5.1. The model is discussed in detail in section 5.2. The presented approach is applied on IEEE 30 bus test system in section 5.3.

5.1 Model Overview

In this approach at first possible strategic scenarios, which may occur in planning horizon, are identified. PDFs of LMPs are computed for each scenario using probabilistic optimal load flow. Then some expansion plans (candidates) are suggested for transmission expansion by the analysis of electric market. Each of the candidates is introduced to the network and the market based criteria are computed for each scenario. The final plan is selected by risk analysis of the solutions. The presented approach can be precised in the following steps:

1) Identifying the set of possible strategic scenarios (refer to 5.2.1)
2) Suggesting candidates for transmission expansion by analyzing electric market (refer to 5.2.2)
3) Computing the market based criteria for each plan in each scenario (refer to 5.2.3)
4) Selecting the final plan by risk assessment of all expansion plans (refer to 5.2.4)
5) Computing the capacity of selected expansion plan (refer to 5.2.5)

5.2 Model in Detail

The above steps are discussed in detail in this section.

5.2.1 Identifying the Set of Possible Strategic Scenarios

Scenario technique is used for modeling non-random uncertainties. The main non-random uncertainty in deregulated power systems is generation expansion / closures, which is not coordinated by transmission expansion planning. To model non-random uncertainties the set of possible future scenarios must be determined. A scenario (futures) is a set of outcomes or realizations of all non-random uncertainties. For example consider the network of section 3.3, which is redrawn in figure 5.1. Suppose there are three possible non-random uncertainties:

- Installation of a 150 MW IPP at bus 2
- Closure of generator of bus 4
- Installation of a 100 MW load at bus 5

Different sets of outcomes can be assumed for the above non-random uncertainties. For example:

- Scenario A: occurrence of all above uncertain events. In this scenario the system consists of the existing network plus a 150 MW IPP in bus 2 minus generator of bus 4 plus a 100 MW load in bus 5
- Scenario B: only occurrence of the first uncertain event. In this scenario the system consists of the existing network plus a 150 MW IPP at bus 2.

Identified scenarios must cover all non-random uncertainties. An occurrence degree is assigned to each scenario to represent the possibility of occurrence of each uncertainty. The designed expansion plan must fulfill the objectives of transmission expansion planning in all scenarios. On the other word, the designed plan must fulfill the planning objectives regardless which scenario happens.

5.2.2 Suggesting Candidates for Transmission Expansion

In the most of transmission expansion planning approaches, at first some candidates are suggested for transmission expansion. Then the best one is selected by evaluating the candidates. In transmission expansion planning, the set of possible expansion plans is very large since between each two buses a new transmission line can be constructed. There are $n(n-1)/2$ candidates for expansion of an n bus network. Most of these candidates do not satisfy the

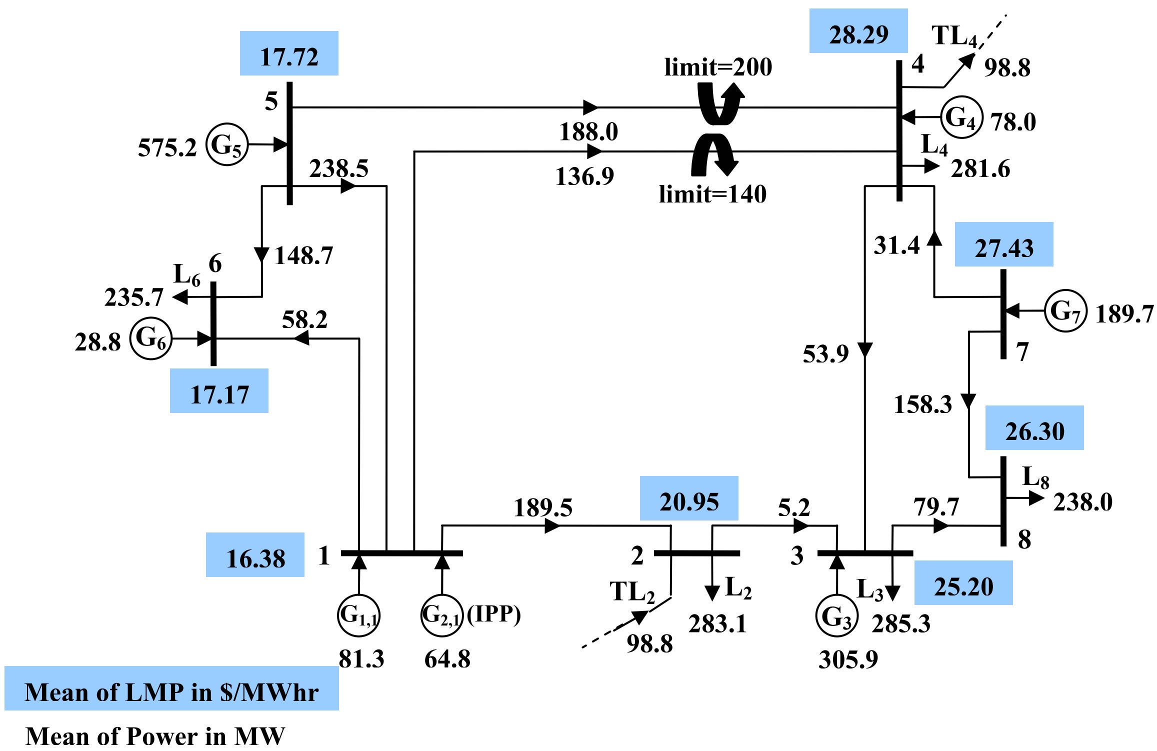


Fig. 5.1 - Test system: eight bus network

objectives of planning. In regulated power systems transmission expansion candidates are suggested based on the technical analysis of transmission network and determination of network bottlenecks. In deregulated power systems expansion candidates must be suggested based on the market analysis. On the other word, providing a non-discriminatory competitive environment must be used as a criterion for suggesting transmission expansion candidates.

In this approach to suggest transmission expansion candidates, at first PDFs of LMPs are computed for the peak load of planning horizon of each scenario. A high mean of LMP at a bus indicates no access to cheap generation. A low mean of LMP indicates access to excess cheap generation and no access to enough loads. Hence, if a new transmission line is constructed between two buses with low and high mean of LMP, the excess cheap generation at low LMP bus will be dispatched and electric energy will flow from low LMP bus to high LMP bus duo to price potential difference. This transmission line has two effects. First, it alleviates the transmission constraints between these two buses and cause to dispatch cheap generation that could not be dispatched because of the transmission constraints. Second, it may decrease LMPs of some high LMP buses or increase LMPs of some low LMP buses. Consequently it decreases transmission constraints and price discrimination among customers. Thus, if a line is added between a low LMP bus and a high LMP bus, competition will be promoted among customers. Three factors are effective in flowing energy from the low LMP bus to the high LMP bus. The first and the most important one is price potential difference between these buses. The second is the quantity of undispatched cheap generation which the low LMP bus has access to it. The third is the quantity of loads which the high LMP bus has access to it. It is not easy to determine how much a bus has access to load or undispatched cheap generation. Therefore, between each two buses that have average LMP difference greater than a specified value (SV), e.g. \$5/MWhr, a new line is suggested as transmission expansion candidate. The set of expansion candidates is equal to the union of expansion candidates in all scenarios.

To determine the set of expansion plans, a proper value must be assigned to SV. It must be a positive real number smaller than the maximum LMP differences among network buses. If a big value is selected for SV, domain of search for the optimal plan decreases and only a few plans will be suggested. Hence, we may lose the optimal plan. For example consider the 8 bus network of figure 5.1. If SV is \$11.5/MWhr, i.e. if between each two buses that have LMP difference greater than \$11.5/MWhr a transmission line is suggested as expansion candidate, only one candidate (line 1-4) is suggested. As it is shown in section 4.4, line 5-4 and line 5-3 are more favorable than line 1-4. Therefore, if SV is \$11.5/MWhr, we lose the optimal plan. If a small value for SV is selected domain of search for the optimal plan increases. Consequently the time of finding the optimal plan increases. Consider the figure 5.1 again. If SV is \$3/MWhr, i.e. if between each two buses that have LMP difference greater than \$3/MWhr a transmission line is suggested as expansion candidate, 20 candidates are suggested for transmission expansion. Although this domain of search contains the optimal plan surly but it takes time to find the optimal plan. Therefore, SV must be selected so that domain of search contains the optimal plan, and it is as small as possible. Since price potential difference is an important factor in flowing electric energy from the low LMP bus to the high LMP bus, the optimal plan is among the plans that have a big LMP difference between their two end buses. Selected value for SV depends on the network. A value between 0.5η and 0.75η is suggested for SV. Where η is the maximum LMP difference among network buses. For example in figure 5.1, the maximum LMP difference is η=\$11.92/MWhr, if SV is selected equal 8, approximately 0.7η, then domain of search has 11 candidates which contains the optimal plan and we need half time with respect to SV = \$3/MWhr to find the optimal plan. If after the first stage of planning i.e. after adding the first optimal plan to the network, still there is considerable average congestion cost or weighted standard deviation of mean of LMP, another plan must be designed. In the next stage of planning, SV must be decreased to have enough candidates.

5.2.3 Computing the Market Based Criteria

After determining the expansion candidates, a market based criterion must be selected for measuring the goodness of expansion candidates. Then, each candidate with the highest possible capacity is added to the network and the selected market based criterion is computed for each scenario.

5.2.4 Risk Assessment of the Expansion Candidates

Suppose N_p is the number of expansion candidates, N_s is the number of scenarios, and $f^{k,l}$ is the value of the selected criterion for plan k in scenario l. In the step 3 of the planning $f^{k,l}$ is computed for each plan in each scenario. Therefore, there is a table of $f^{k,l}$ for $k = 1, 2, \ldots, N_p$ and $l = 1, 2, \ldots, N_s$ and the final plan must be selected. Table 5.1 shows a typical table for the selected criterion. If in scenario l, $f^{m,l}$ is smaller than $f^{k,l}$ for $k = 1, 2, \ldots, N_p$, $k \neq m$, then plan m is the optimal plan of scenario l. If plan m is the optimal plan in all scenarios i.e. if $f^{m,l}$ is smaller than $f^{k,l}$ for $k = 1, 2, \ldots, N_p$, $k \neq m$, and $l = 1, 2, \ldots, N_s$, then plan m is selected as the final plan. Usually above condition is not fulfilled i.e. the optimal plans of different scenarios are not the same. Therefore, a criterion must be used for selecting the final plan. As it was discussed in section 2.1.1, the criteria expected cost, minimax regret, Laplace, Von Neumann-Morgenstern, Hurwicz, Pareto-optimal, Robustness, and β-robustness are used for selecting the final plan in scenario technique (see examples of appendix A). According to literature survey, section 2.1.1, in cases that scenarios are non-random, minimax regret criterion is more suitable than other ones for static planning. In the rest of this subsection minimax regret criterion is described. Before continuing, note that here we are discussing about the criteria which are used for selecting the final plan from the table of goodness measuring criterion. These criteria must not be confused with the market criteria were presented in chapter 4 for measuring the goodness of transmission plans.

Table 5.1- Typical table for the goodness measuring criterion for different expansion plans in different scenarios

	Scenario 1	**Scenario 2**	**…**	**Scenario N_s**
Plan 1	$f^{1,1}$	$f^{1,2}$	…	$f^{1,Ns}$
Plan 2	$f^{2,1}$	$f^{2,2}$	…	$f^{2,Ns}$
⋮	⋮	⋮	⋱	⋮
Plan N_p	$f^{Np,1}$	$f^{Np,2}$	…	$f^{Np,Ns}$

Regret is a measure of risk. Regret of plan *k* in scenario *l* is defined as the difference between the cost of plan *k* and the cost of optimal plan of scenario *l*. In definition of regret "cost" means any criterion that can be used for measuring the goodness of expansion plans. Regret is formulated as bellow:

$$r^{k,l} = f^{k,l} - f^{op,l} \tag{5.1}$$

with:

$r^{k,l}$	regret of plan *k* in scenario *l*
$f^{k,l}$	value of the selected market based criterion for plan *k* in scenario *l*
$f^{op,l}$	value of selected market based criterion for the optimal plan of scenario *l*

Minimax regret selects the plan which minimizes the maximum weighted regret over different scenarios i.e.:

$$\underset{k}{Min}\left\{\underset{l}{Max}\left(\upsilon^{l} r^{k,l}\right)\right\} \tag{5.2}$$

with:

υ^{l}	occurrence degree of scenario *l*

See the example of appendix A for more detail on minimax regret criterion.

5.2.5 Capacity of New Transmission Lines

After determining the final expansion plans, the capacity of the selected plans must be determined. The capacities of selected transmission lines are determined using the PDFs of power of selected transmission lines in different scenarios. The capacities are determined so that the probability of violating the limits of selected lines is less than one percent in each scenario during the peak load of planning horizon.

5.2.6 Transmission Expansion Planning Algorithm

The algorithm of presented transmission expansion planning approach is as bellow:

1. Identify the set of possible strategic scenarios and their occurrence degrees.
2. Suggest candidates for transmission expansion.
    2.1. Compute PDFs of LMPs for the existing network in different scenarios.
    2.2. Select a value for SV.

2.3. Determine the set of expansion candidates. If the selected value for SV do not suggest enough candidates decrease SV and determine the set of transmission candidates again. If the selected value for SV suggests many candidates increase SV and determine the set of transmission candidates again to eliminate the ineffective candidates.

3. Compute the planning criterion for each plan in each scenario.

   Introduce each expansion candidate with the highest possible capacity to the network, and compute the selected market based criterion for each expansion plan in each scenario.

4. Select the final plan by risk assessment of all expansion plans.

   4.1. Compute regret of each expansion plan in each scenario.

   4.2. Select the plan which has minimax regret as the final plan.

5. If the final plan does not decrease the selected market based criterion noticeably, decrease the SV and go to step 2.3.

6. If market based criterion still has noticeable value and if there is enough budget for more transmission expansion, add the final plan to the network and go to step 2.3.

7. Compute the capacity of new transmission lines.

5.3 Case Study: IEEE 30 bus test system

In this section the proposed approach is applied to the IEEE 30 bus test system [62]. Figure 5.3 shows the single line diagram of IEEE 30 bus system. Characteristics of transmission lines are given in table 5.2. Characteristics generators and loads for the peak load of planning horizon are given in tables 5.3 and 5.4. As shown tables 5.3 and 5.4, a normal (Gaussian) PDF is assigned to the load of each bus and bid of each generator. It is assumed that the unavailability of each transmission line is equal to 0.001.

Standard deviation of mean of LMP and average congestion cost are equal to \$2.6351/MWhr and \$2240.8/hr for the existing network during the peak load of planning horizon. These values seem to be high and indicate that the network needs a few lines to have a flat price profile and zero congestion cost.

The desire is to have zero congestion cost network and flat price profile. If average congestion cost is selected as planning criterion and it is tried to reduce average congestion cost by expansion planning, other presented criteria will reduce too. If the expansion planning is

Table 5.2 – Characteristics of transmission lines of IEEE 30 bus test system

Line No.	From Bus	To Bus	Resistance (pu)	Reactance (pu)	Limit (MW)	Unavailability
1	1	2	0.0192	0.0575	130	0.001
2	1	3	0.0452	0.1852	130	0.001
3	2	4	0.0570	0.1737	65	0.001
4	3	4	0.0132	0.0379	130	0.001
5	2	5	0.0472	0.1983	130	0.001
6	2	6	0.0581	0.1763	65	0.001
7	4	6	0.0119	0.0414	90	0.001
8	5	7	0.0460	0.1160	70	0.001
9	6	7	0.0267	0.0820	130	0.001
10	6	8	0.0120	0.0420	32	0.001
11	6	9	0.0000	0.2080	65	0.001
12	60	10	0.0000	0.5560	32	0.001
13	9	11	0.0000	0.2080	65	0.001
14	9	10	0.0000	0.1100	65	0.001
15	4	12	0.0000	0.2560	65	0.001
16	12	13	0.0000	0.1400	65	0.001
17	12	14	0.1231	0.2559	32	0.001
18	12	15	0.0662	0.1304	32	0.001
19	12	16	0.0945	0.1987	32	0.001
20	14	15	0.2210	0.1997	16	0.001
21	16	17	0.0824	0.1932	16	0.001
22	15	18	0.1070	0.2185	16	0.001
23	18	19	0.0639	0.1292	16	0.001
24	19	20	0.0340	0.0680	32	0.001
25	10	20	0.0936	0.2090	32	0.001
26	10	17	0.0324	0.0845	32	0.001
27	10	21	0.0348	0.0749	32	0.001
28	10	22	0.0727	0.1499	32	0.001
29	21	22	0.0116	0.0236	32	0.001
30	15	23	0.1000	0.2020	16	0.001
31	22	24	0.1150	0.1790	16	0.001
32	23	24	0.1320	0.2700	16	0.001
33	24	25	0.1885	0.3292	16	0.001
34	25	26	0.2544	0.3800	16	0.001
35	25	27	0.1093	0.2087	16	0.001
36	28	27	0.0000	0.3960	65	0.001
37	27	29	0.2198	0.4153	16	0.001
38	27	30	0.3202	0.6027	16	0.001
39	29	30	0.2399	0.4530	16	0.001
40	8	28	0.6360	0.2000	32	0.001
41	6	28	0.0169	0.0599	32	0.001

Table 5.3- Characteristics of generators of IEEE 30 bus test system

Bus No.	Min Power (MW)	Max Power (MW)	PDF of Bids ($/MWhr)	Unavailability
1	0	200	N~(11.5, 1.2)	0.02
2	0	200	N~(11.0, 1.0)	0.02
3	0	50	N~(10.0, 1.0)	0.02
8	0	130	N~(11.5, 1.3)	0.02
11	0	120	N~(11.5, 1.1)	0.02
13	0	120	N~(16.0, 1.4)	0.02
14	0	160	N~(16.0, 1.5)	0.02
15	0	100	N~(17.0, 1.6)	0.02
18	0	100	N~(17.0, 1.6)	0.02
22	0	150	N~(16.0, 1.5)	0.02
23	0	150	N~(16.0, 1.4)	0.02
27	0	120	N~(22.0, 2.0)	0.02

* S_{base} = 100 MVA, V_{base} = 135 KV

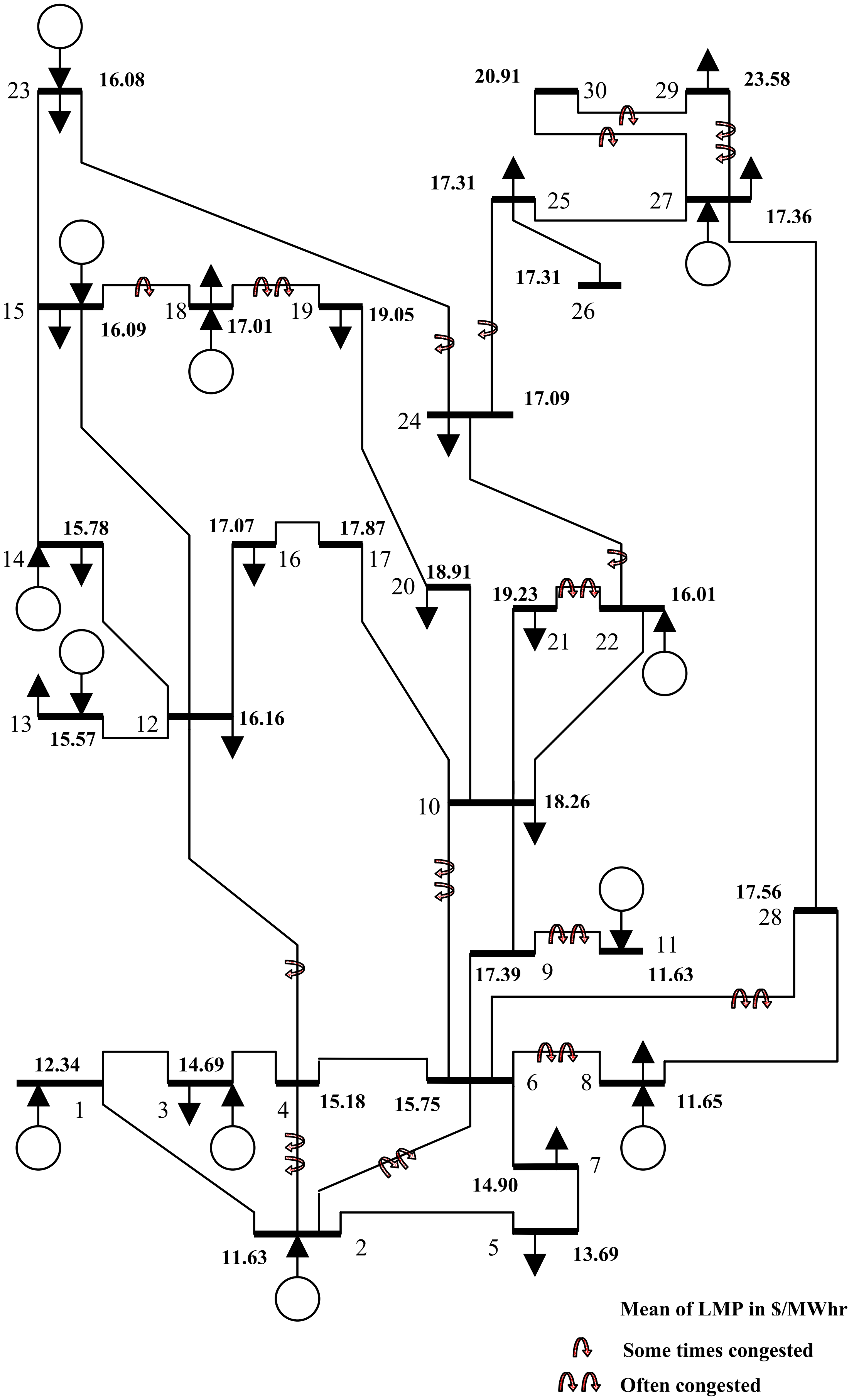


Fig. 5.3- Single line diagram of IEEE 30 bus system

Table 5.4- Characteristics of loads of IEEE 30 bus test system

Bus No.	Min (MW)	PDF of Load (MW)	Bid ($/MWhr)	Unavailability
3	0	N~(160, 12)	15	0.05
5	0	N~(85, 7.5)	14	0.05
7	0	N~(50, 5)	15	0.05
8	0	N~(25, 2)	17	0.05
10	0	N~(190, 15)	20	0.05
12	0	N~(50, 4)	18	0.05
13	0	N~(20, 2)	19	0.05
14	0	N~(50, 4.5)	17	0.05
15	0	N~(50, 5)	16	0.05
16	0	N~(9, 0.5)	20	0.05
8	0	N~(35, 2)	21	0.05
19	0	N~(17, 0.5)	23	0.05
20	0	N~(60, 4.5)	17	0.05
21	0	N~(34, 2.5)	19	0.05
23	0	N~(85, 7.5)	22	0.05
24	0	N~(9, 0.6)	25	0.05
25	0	N~(9, 0.2)	25	0.05
27	0	N~(27, 2)	23	0.05
29	0	N~(35, 2.5)	24	0.05

continued till reach a zero congestion cost network, we will also have a flat price profile. Vice versa, if standard deviation of mean of LMP (or weighted standard deviation of mean of LMP) is used as planning criterion and it is tried to reduce standard deviation of mean of LMP by expansion planning, other criteria will reduce and after achieving a flat price profile we will also have zero congestion cost (see (4.2)). Planning criteria propose different paths (expansion plans) to achieve flat price profile or zero congestion cost. To determine the impacts of reduction of one criterion on the other criteria, and to determine which criterion leads to zero congestion cost and flat price profile at minimum cost or at minimum number of expansion plans, transmission expansion planning is performed eight times (stages) under different criteria. For each criterion, after determining the minimax regret plan, it is added to the network and the approach is repeated. At the first stage of planning between each two buses which have average LMP difference greater than SV=$5/MWhr a new line is suggested as transmission candidate. As new lines are added to the network, price profile becomes flatter. Therefore, number of candidates for the next planning stages decreases. In the stages that suggested candidates do not improve the selected criterion or in the stages that only a few candidates are suggested, SV is decreased to have reasonable number of candidates. To determine the effects of non-random uncertainties on the performance of market based criteria expansion planning is performed under two different assumptions: There is not any non-random uncertainty, and there is non-random uncertainty.

5.3.1 Case 1: There Is Not Any Non-random Uncertainty

In this case there is only one scenario, the scenario which is shown in tables 5.3 and 5.4. Therefore, the minimax regret plan and the optimal plan are the same. Transmission planning is performed under the following market based criteria:

a) $\sigma_{\mu_{lmp}}$: Standard deviation of mean of LMP (SML)

b) $\sigma_{\mu_{lmp}, w=P_g}$: Standard deviation of mean of LMP weighted with mean of generation power (WG)

c) $\sigma_{\mu_{lmp}, w=P_d}$: Standard deviation of mean of LMP weighted with mean of load (WD)

d) $\sigma_{\mu_{lmp}, w=P_g+P_d}$: Standard deviation of mean of LMP weighted with mean of sum of generation power and load (WGD)

e) μ_{tcc}^{k}: Average congestion cost (ACC)

f) μ_{tlp}^{k}: Average load payment (ALP)

Table 5.5 shows the result of planning under SML criterion. In this table rows 1-4 show SV, number of suggested candidates (NC), optimal plan (OP), and capacity of optimal plan (COP) at different stages of planning. Rows 5-10 show the values of different market based criteria in different stages of planning if SML is used as planning criterion. Consider the first stage of planning (column 3 of table 5.5). At first stage of planning SV is \$5/MWhr and 88 candidates are suggested for transmission expansion. If SML is used as planning criterion line 22-29 is the optimal expansion plan. Capacity of this line must be 60 MW in order to ensure the probability of violating its limit is less than one percent. If line 22-29 is added to the network, standard deviation of mean of LMP reduces from \$2.6351/MWhr to \$2.0798/MWhr and average congestion cost reduces from \$2240.8/hr to \$2023.6/hr. At fourth stage of planning with SV = \$5/MWhr only 8 candidates are suggested. In order to avoid from losing the optimal plan, SV reduces to \$4/MWhr. Tables 5.6-5.10 shows the results of planning under other market based criteria. In tables 5.5-5.10 smaller SV indicates flatter price profile since SV is reduced when enough candidates are not suggested for transmission expansion. At a constant SV, smaller number of candidates indicates flatter price profile since number of candidates is equal to number of pairs of buses which have LMP difference greater than SV.

Figure 5.4 shows how SML changes in different stages of planning when SML, WG, WD, WGD, ACC, or ALP are used as planning criterion. Figures 5.5- 5.9 show how WG, WD, WGD, ACC, and ALP change in different stages of planning. The following conclusions can be deduced from these figures:

- If ACC is used as planning criterion:
  - the minimum value of SML, or the flattest price profile, will be achieved after 3 stage of planning (figure 5.4). Note that after one stage of planning, the network configuration may be different under different criteria. Therefore, using SML as planning criterion does not lead to the flattest price profile necessarily.
  - the minimum WG will be achieved after 2 stage of planning (figure 5.5).
  - the minimum WD will be achieved after 5 stage of planning (figure 5.6).
  - the minimum WGD will be achieved after 2 stage of planning (figure 5.7).
  - the minimum ACC will be achieved after 1 stage of planning (figure 5.8).

  Therefore, the most decrease in SML, WG, WD, WGD, and ACC will be achieved after a few stage of planning if ACC is used as planning criterion and hence ACC is the most effective criterion.

- If ACC is used as planning criterion, SML overshoot in stage 1 (figure 5.4). This means in this network competition will be discouraged if one stage of planning is performed under ACC. Therefore, if planners are restricted to perform only one stage planning because of the budget limitations, ACC is not a proper criterion for transmission planning.

- If ALP is used as planning criterion, price profile will deviate from flatness (figure 5.4) and congestion cost will decrease just a little (figure 5.8). Hence, ALP is not a proper criterion for expansion planning in deregulated power system.

- WGD causes acceptable decrease in other criteria if it is used as planning criterion Hence, WGD is a suitable criterion for transmission expansion planning in deregulated power systems.

Table 5.5 – Result of planning under SML criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	---	5	5	5	4	2	2	2	2
NC	---	88	38	13	39	71	63	91	11
OP	---	22-29	5-10	11-20	8-12	16-18	1-6	7-21	7-24
COP	---	60	145	159	185	36	267	116	47
SML	2.6351	2.0798	1.5456	1.3542	1.1378	1.0931	0.9276	0.6303	0.4580
WG	1.7458	1.4977	1.3868	1.2371	1.1302	1.1355	0.5777	0.3732	0.3037
WD	1.0686	0.9279	0.5162	0.5026	0.3676	0.3127	0.4544	0.3219	0.2862
WGD	2.0468	1.7618	1.4797	1.3353	1.1885	1.1778	0.7350	0.4928	0.4173
ACC	2240.8	2023.6	1707.6	1381.0	1155.3	1145.4	529.3	340.2	293.8
ALP	12169.9	12276.7	11280.1	11589.6	12129.6	12081.0	12466.7	12373.7	12142.6

* Dimension of SV, SML, WG, WD, and WGD is $/MWhr, dimension of COP is MW, and dimension of ACC and ALP is $/hr

Table 5.6 – Result of planning under WG criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	---	5	5	5	5	5	4	2	1
NC	---	88	87	74	49	30	18	49	74
OP	---	1-28	11-10	8-9	7-29	28-12	12-20	9-18	5-23
COP	---	298	197	161	67	251	121	94	158
SML	2.6351	2.7769	2.3987	2.1865	1.5392	1.2539	0.7579	0.3740	0.2447
WG	1.7458	1.3075	1.0204	0.8467	0.6498	0.6025	0.3439	0.2264	0.0953
WD	1.0686	1.1659	0.9073	0.8029	0.4150	0.6123	0.4120	0.2433	0.1258
WGD	2.0468	1.7519	1.3655	1.1669	0.7710	0.8590	0.5367	0.3323	0.1578
ACC	2240.8	1870.6	1103.4	888.9	636.6	479.0	286.8	184.3	169.8
ALP	12169.9	11515.9	11250.5	11543.6	11281.2	12029.6	12259.5	12193.5	11452.3

* Dimension of SV, SML, WG, WD, and WGD is $/MWhr, dimension of COP is MW, and dimension of ACC and ALP is $/hr

Table 5.7 – Result of planning under WD criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	---	5	5	5	3	3	3	1	1
NC	---	88	44	20	57	51	58	171	164
OP	---	7-29	8-10	11-8	5-20	1-28	27-18	5-23	17-25
COP	---	68	322	164	113	92	60	156	35
SML	2.6351	2.1464	1.5620	1.2420	1.1241	1.3774	1.3252	1.4274	1.4006
WG	1.7458	1.5177	1.3560	1.1318	1.1166	0.6106	0.6099	0.6120	0.6029
WD	1.0686	0.8942	0.5702	0.4317	0.3508	0.3352	0.2394	0.2036	0.1688
WGD	2.0468	1.7615	1.4710	1.2113	1.1704	0.6965	0.6552	0.6450	0.6261
ACC	2240.8	2057.4	1415.1	1011.4	1064.6	613.0	591.3	633.4	601.3
ALP	12169.9	11685.9	12248.5	12182.6	121430	11251.0	11110.1	10816.0	10755.2

* Dimension of SV, SML, WG, WD, and WGD is $/MWhr, dimension of COP is MW, and dimension of ACC and ALP is $/hr

Table 5.8 – Result of planning under WGD criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	---	5	5	5	5	5	3	2	1
NC	---	88	87	74	42	19	53	46	97
OP	---	1-28	11-10	12-29	8-9	28-29	12-20	11-18	5-23
COP	---	305	181	63	143	281	122	92	182
SML	2.6351	2.7769	2.3987	1.8132	1.4570	1.1188	0.7257	0.3815	0.1882
WG	1.7458	1.3075	1.0204	0.9404	0.7395	0.4913	0.3107	0.2147	0.0782
WD	1.0686	1.1659	0.9073	0.6548	0.4179	0.5723	0.3892	0.2356	0.1125
WGD	2.0468	1.7519	1.3655	1.1459	0.8494	0.7542	0.4980	0.3188	0.1370
ACC	2240.8	1870.6	1103.4	9.4594	721.4	365.9	270.1	183.9	142.6
ALP	12169.9	11515.9	11250.5	11160.0	11472.0	12186.3	12358.8	12191.7	11424.0

* Dimension of SV, SML, WG, WD, and WGD is $/MWhr, dimension of COP is MW, and dimension of ACC and ALP is $/hr

Table 5.9 – Result of planning under ACC criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	---	5	5	5	4	2.5	1.5	1	1
NC	---	88	125	24	10	21	9	49	17
OP	---	1-10	11-29	11-20	8-23	10-18	23-16	10-15	5-14
COP	---	367	72	117	179	102	51	122	135
SML	2.6351	3.3341	1.7463	1.1200	0.7472	0.4107	0.3088	0.1868	0.1319
WG	1.7458	1.4272	0.8542	0.6426	0.3123	0.1930	0.1556	0.0993	0.0536
WD	1.0686	1.3245	0.7525	0.5622	0.3782	0.2203	0.1751	0.1090	0.0682
WGD	2.0468	1.9471	1.1383	0.8538	0.4905	0.2929	0.2342	0.1475	0.0868
ACC	2240.8	1089.2	673.1	449.6	277.9	189.1	168.1	128.0	96.3
ALP	12169.9	11998.5	11589.1	12114.7	11944.7	11698.0	11619.4	11597.4	11474.7

* Dimension of SV, SML, WG, WD, and WGD is $/MWhr, dimension of COP is MW, and dimension of ACC and ALP is $/hr

Table 5.10 – Result of planning under ALP criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	---	5	5	5	5	5	5	4	4
NC	---	88	112	138	118	109	119	196	179
OP	---	2-28	11-21	6-29	1-23	23-18	25-20	18-14	22-30
COP	---	74	127	82	303	168	22	111	14
SML	2.6351	3.0212	3.3180	3.0446	2.8604	3.0653	3.1446	3.0640	2.7448
WG	1.7458	1.4681	1.3303	1.2620	1.2988	1.2376	1.4443	1.4396	1.2597
WD	1.0686	1.1534	1.3741	1.1137	1.2042	1.2310	1.3005	1.2894	1.1566
WGD	2.0468	1.8670	1.9126	1.6831	1.7711	1.7456	1.9436	1.9326	1.7102
ACC	2240.8	2093.1	1893.7	1512.9	1408.7	1441.2	1553.7	1611.5	1489.3
ALP	12169.9	10822.3	9349.0	8682.9	8503.3	8236.9	8214.9	8013.0	7956.3

* Dimension of SV, SML, WG, WD, and WGD is $/MWhr, dimension of COP is MW, and dimension of ACC and ALP is $/hr

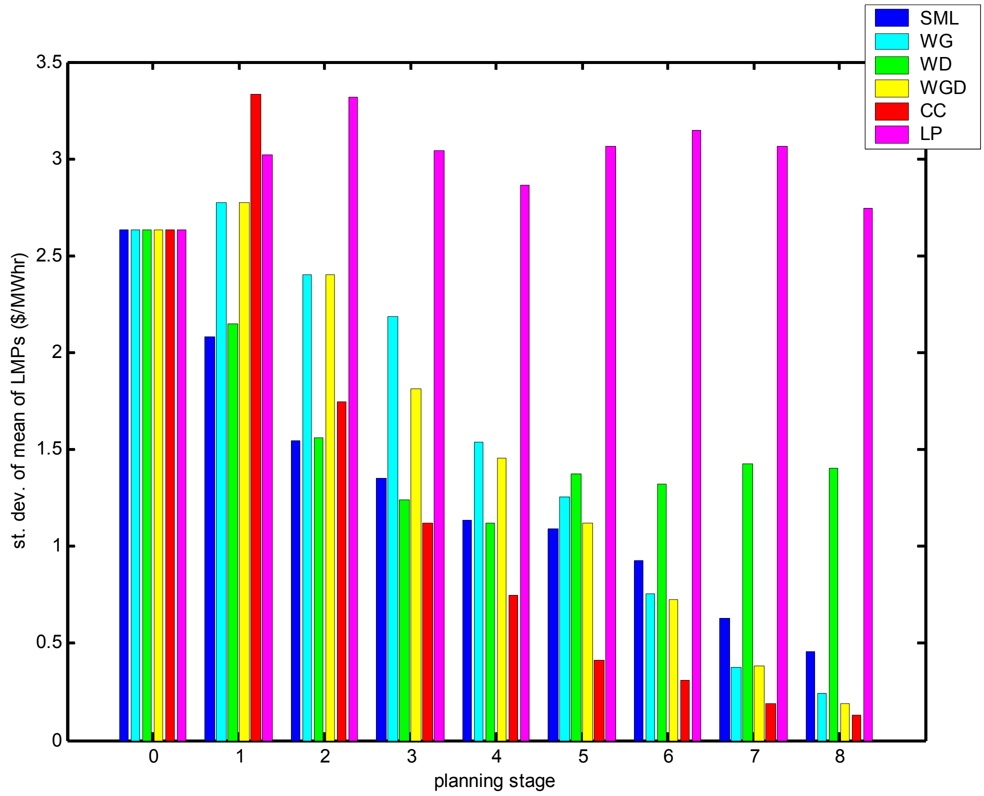


Fig. 5.4 (a) - Values of SML at different stages of planning (In each stage there are six bars. These bars show the values of SML when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion respectively.)

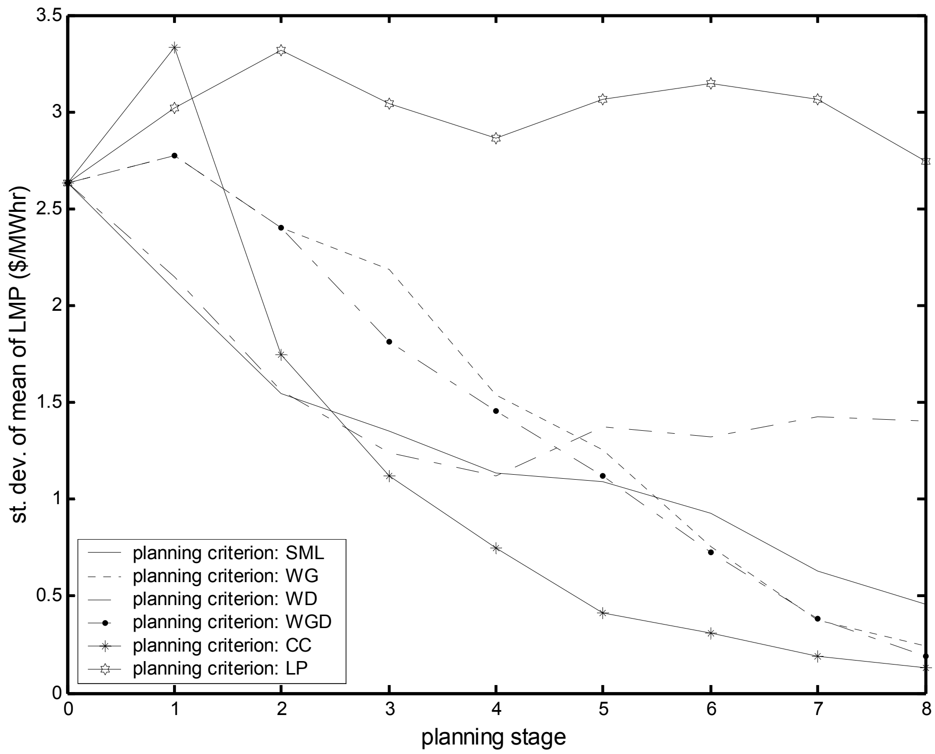


Fig. 5.4 (b) - Values of SML at different stages of planning when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion.

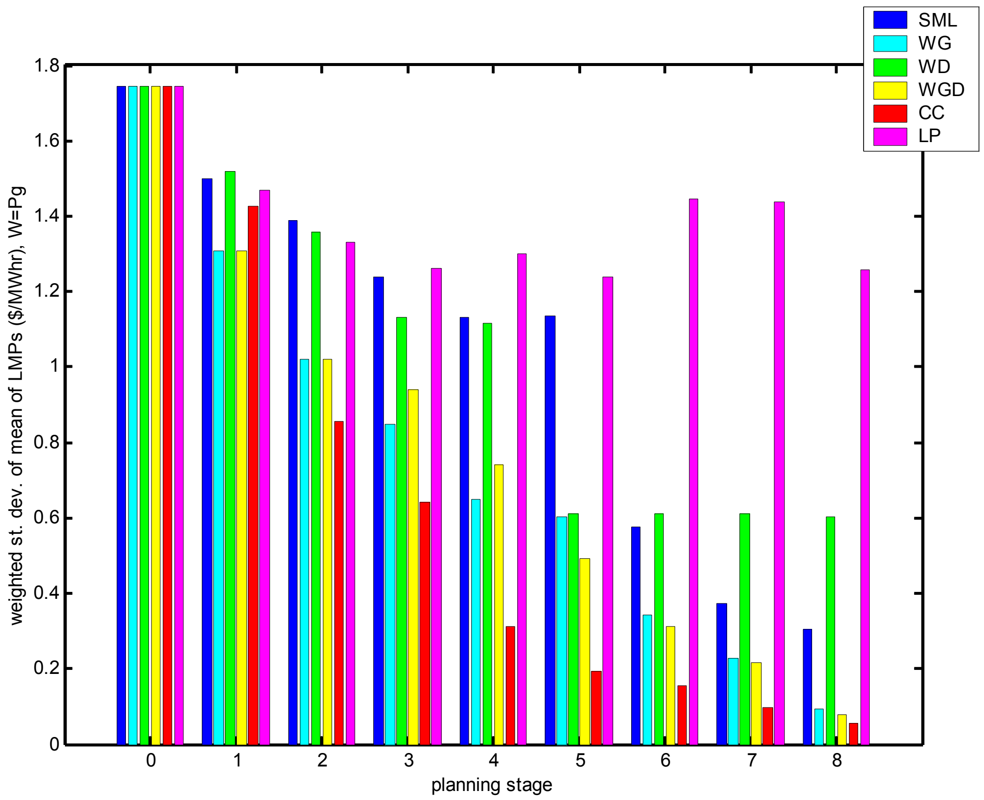


Fig. 5.5 (a) - Values of WG at different stages of planning (In each stage there are six bars. These bars show the values of WG when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion respectively.)

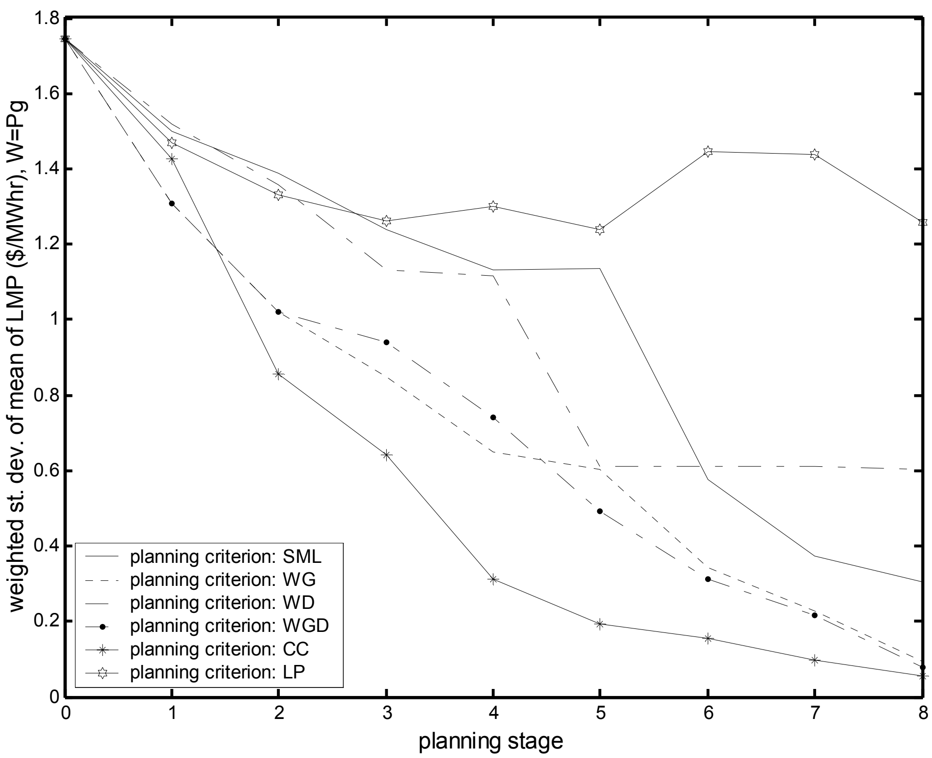


Fig. 5.5 (b) - Values of WG at different stages of planning when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion.

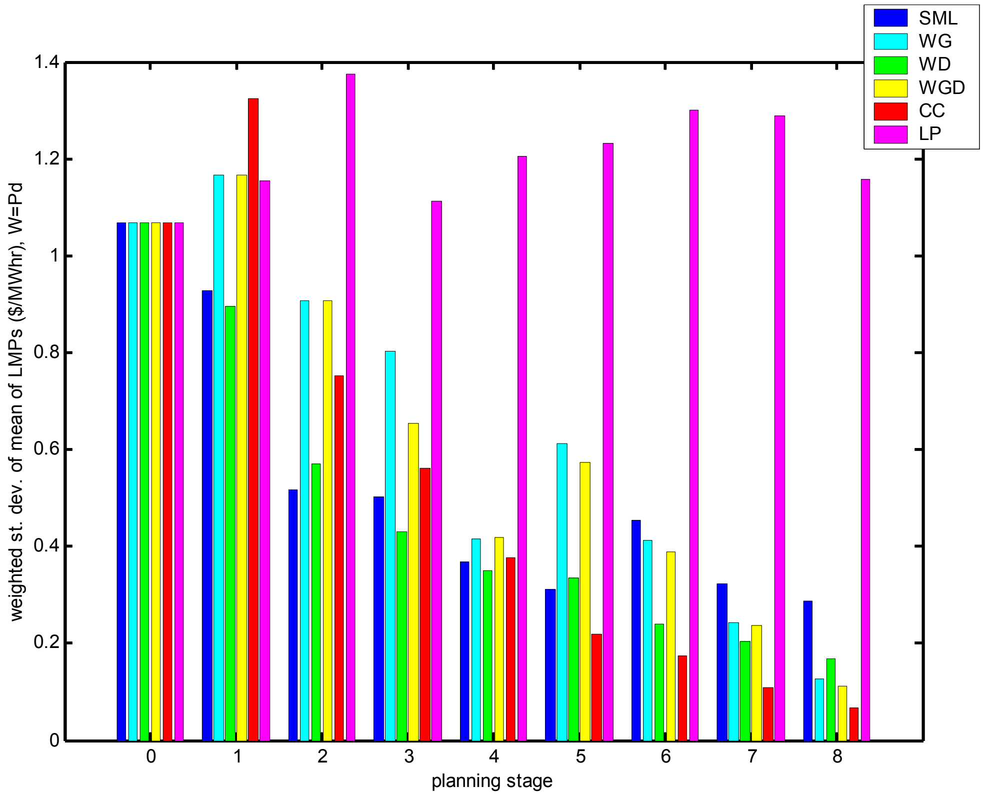


Fig. 5.6 (a) - Values of WD at different stages of planning (In each stage there are six bars. These bars show the values of WD when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion respectively.)

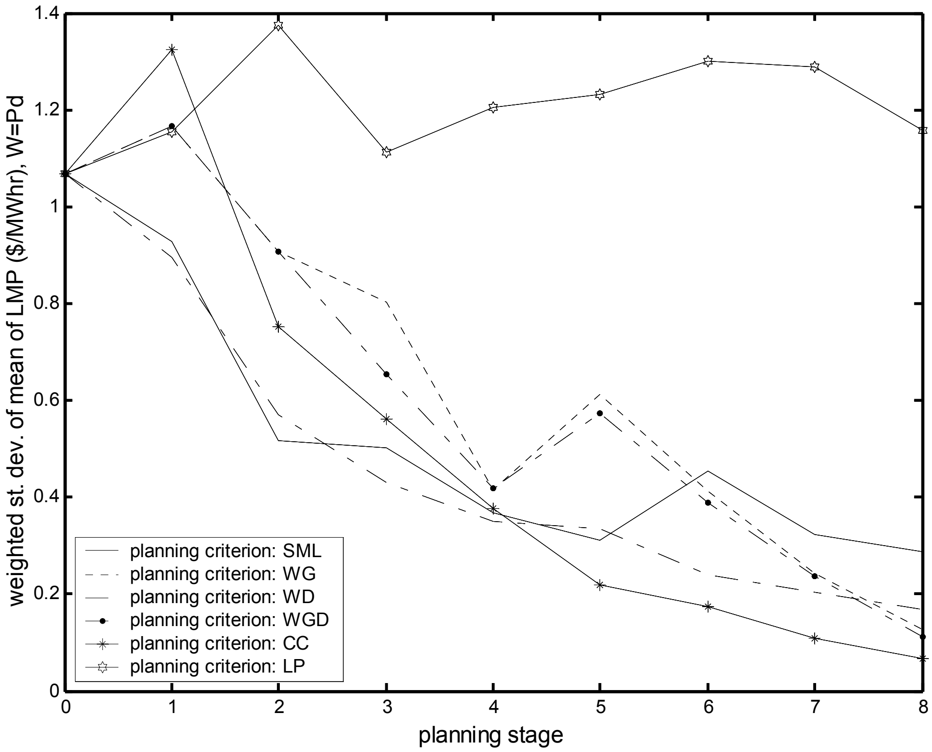


Fig. 5.6 (b) - Values of WD at different stages of planning when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion.

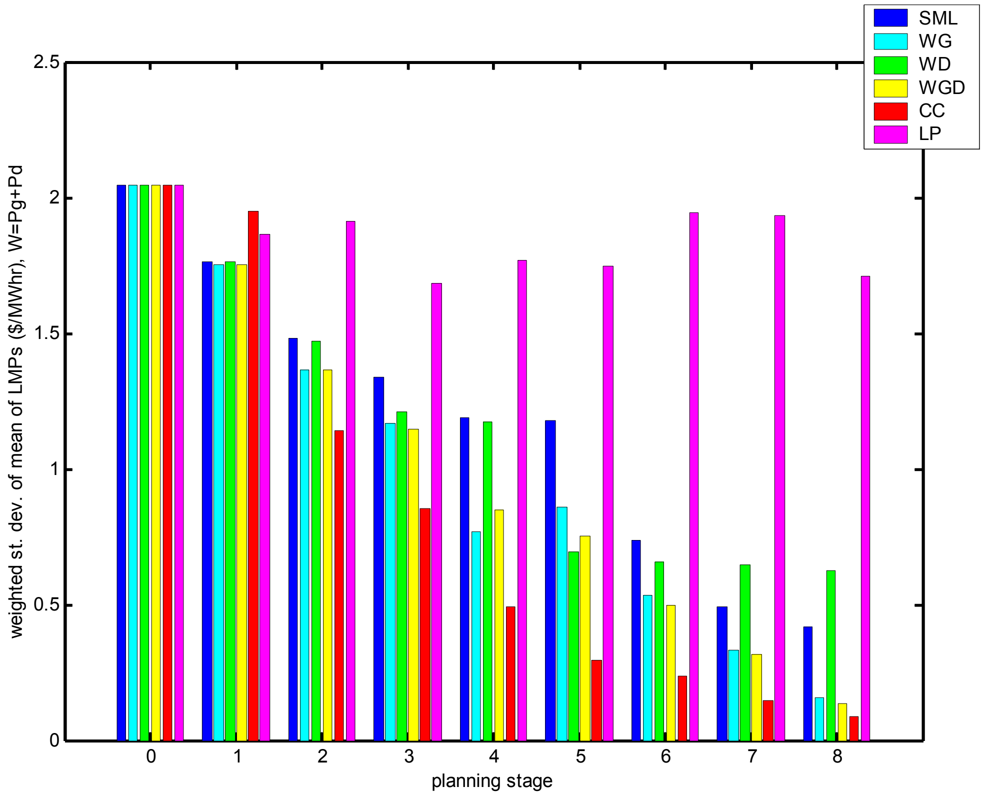


Fig. 5.7 (a) - Values of WGD at different stages of planning (In each stage there are six bars. These bars show the values of WGD when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion respectively.)

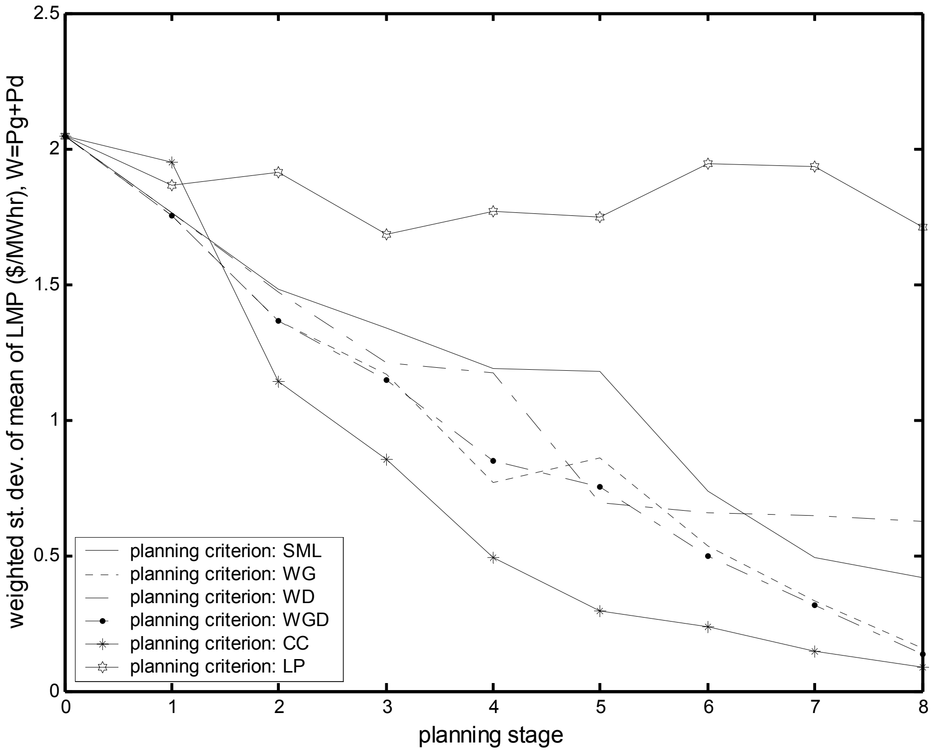


Fig. 5.7 (b) - Values of WGD at different stages of planning when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion.

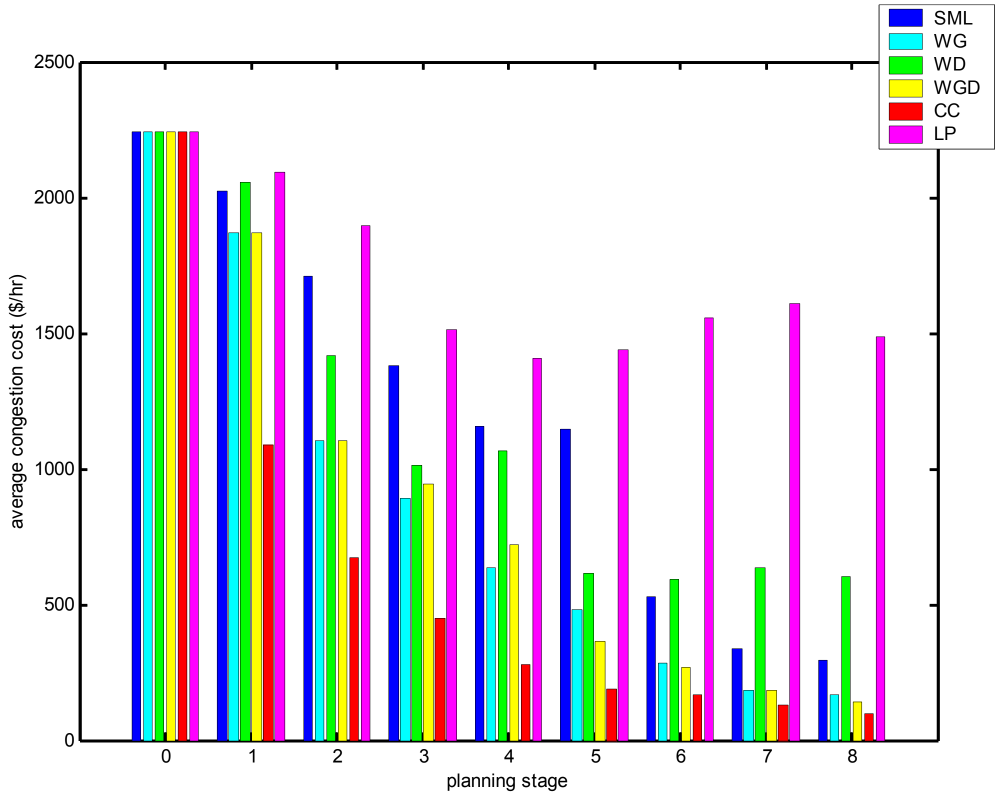


Fig. 5.8 (a) - Values of ACC at different stages of planning (In each stage there are six bars. These bars show the values of ACC when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion respectively.)

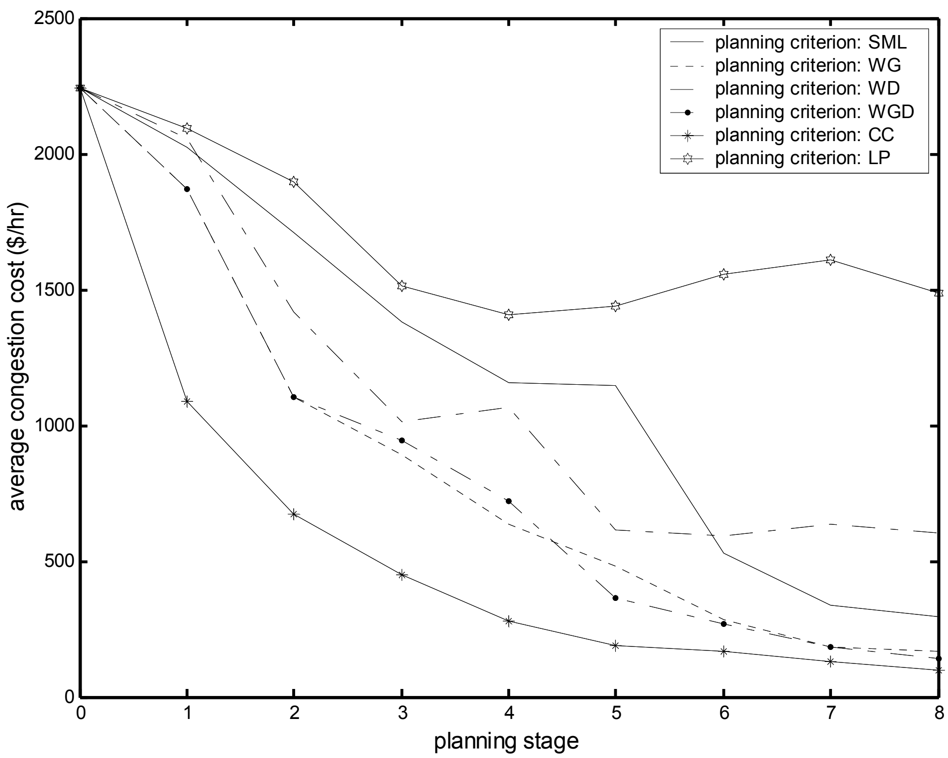


Fig. 5.8 (b) - Values of ACC at different stages of planning when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion.

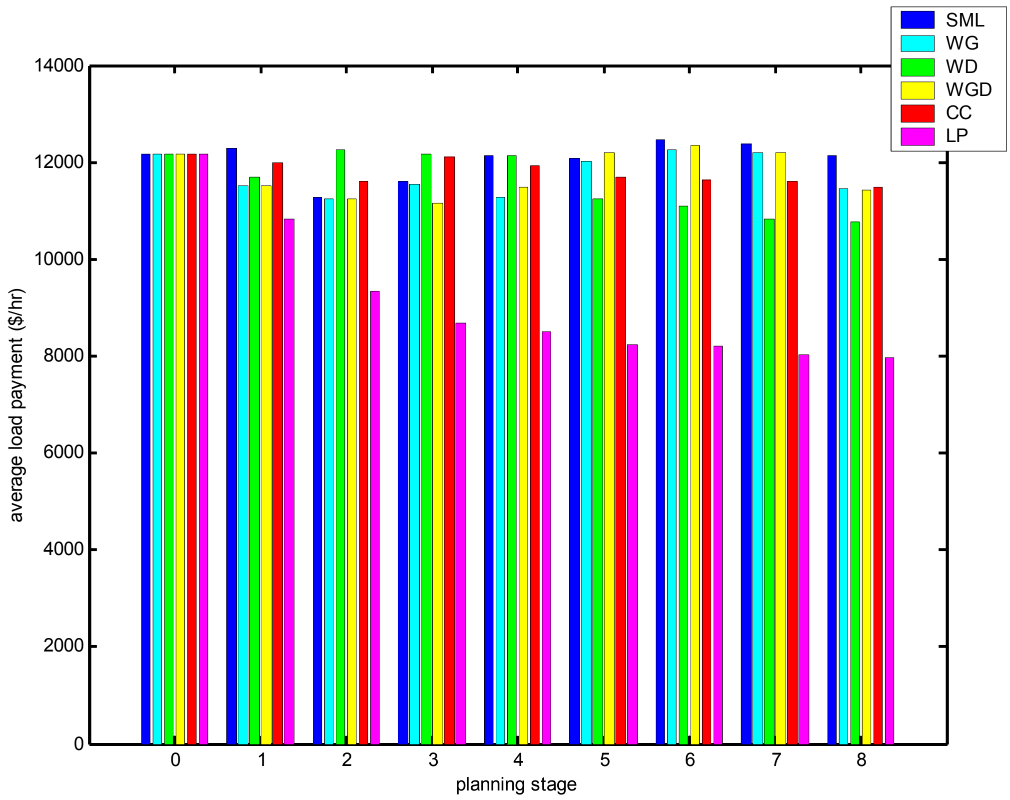


Fig. 5.9 (a) - Values of ALP at different stages of planning (In each stage there are six bars. These bars show the values of ALP when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion respectively.)

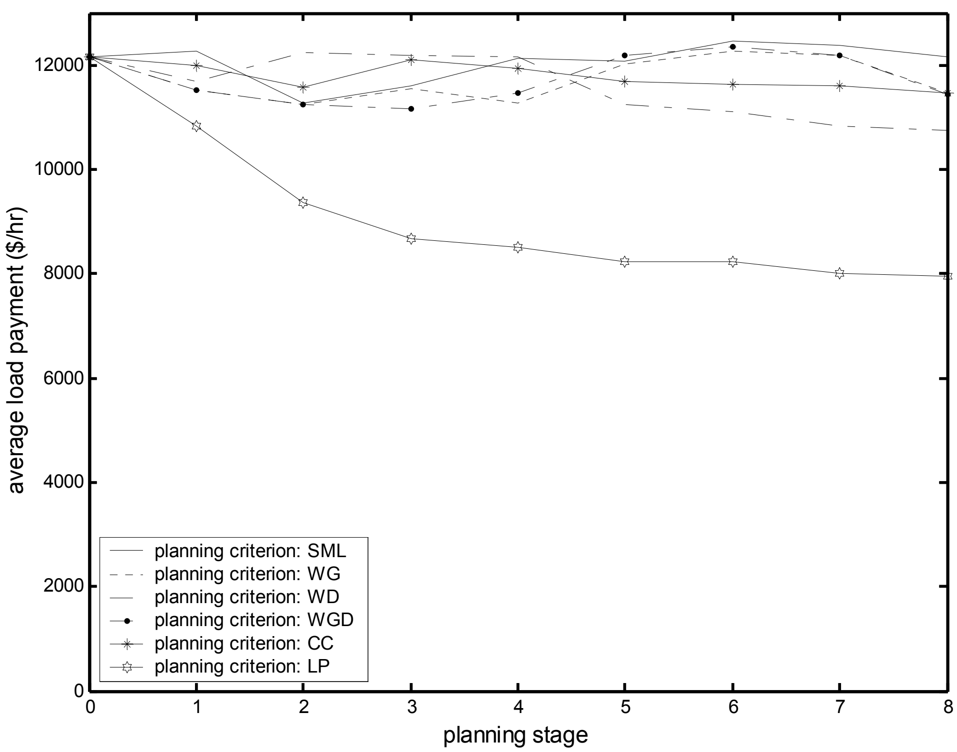


Fig. 5.9 (b) - Values of ALP at different stages of planning when SML, WGD, WG, WD, ACC, or ALP is used as planning criterion.

5.3.2 Case 2: There Is Non-random Uncertainty

In this case it is assumed that the following non-random uncertainties have been identified by planners:

- A generator may be added at bus 10 of the network.
- An IPP may be added at bus 16 of the network.
- Load of bus 24 may be change.

Characteristics new generator, IPP, and load are given in tables 5.11 and 5.12. To take into account these non-random uncertainties in transmission expansion planning, the following scenarios are defined:

- Scenario 1: base case (scenario which is shown in tables 5.3 and 5.4)
- Scenario 2: base case plus the new generator
- Scenario 3: base case plus the load change
- Scenario 4: base case plus the IPP
- Scenario 5: base case plus the new generator and load change
- Scenario 6: base case plus the new generator and IPP
- Scenario 7: base case plus the load change and IPP
- Scenario 8: base case plus the new generator, load change, and IPP

It is assumed that all above scenarios have the same occurrence degree. SML, WGD, and ACC are used as planning criterion. In other word, SML, WGD, and ACC are used as cost function of risk analysis.

Table 5.13 shows the result of planning under SML criterion. In this table rows 1-4 show SV, number of candidates (NC), minimax regret plan (MRP), and capacity of minimax regret plan (CMP) at different stages of planning. Rows 5-12 show the values of SML at different scenarios and different stages of planning when SML is used as planning criterion. Rows 13-20 show the values of WGD at different scenarios and different stages of planning when SML

Table 5.11 – Characteristics of uncertain new generator and IPP

Type	Bus No.	Min Power (MW)	Max Power (MW)	PDF of Bid ($/MWhr)	Unavailability
Gen.	10	0	150	N~(11, 1.2)	0.02
IPP	16	0	N~(80, 20)	N~(13, 1.5)	0.02

Table 5.12 - Characteristics of uncertain new load

Bus No.	Min Power (MW)	PDF of Load (MW)	Bid ($/MWhr)	Unavailability
24	0	N~ (50, 10)	17	0.05

is used as planning criterion. Rows 21-28 show the values of ACC at different scenarios and different stages of planning when SML is used as planning criterion. Table 5.14 and 5.15 show the results of planning under WGD, and ACC criteria.

Figure 5.10-(a) shows the values of SML in different scenarios and different stages of planning. At each stage there are three bars. These bars, from left to right, show the maximum values of SML over different scenarios when SML, WGD or ACC is used as planning criterion respectively. There are eight signs over each bar which show the values of SML in different scenarios. Figure 5.10-(b) shows the maximum, mean, and minimum of SML over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion. Figure 5.10-(c) shows the maximum of SML over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion. Figures 5.11-5.12 show the values of WGD, and ACC in different scenarios and different stage of planning when SML, WGD, and ACC are used as expansion planning criterion.

Figures 5.10 (a)-(c) show that:

- Approximately the smallest values of SML, the flattest price profile, in different scenarios are achieved when WGD is used as planning criterion.
- If ACC is used as planning criterion, SML will overshoot at first stage of planning in all scenarios.
- If ACC is used as planning criterion, in some stage of planning SML varies in a wide range over different scenarios. This means a high risk for planners.

Figures 5.11 (a)-(c) show that:

- If ACC is used as planning criterion, WGD will overshoot at first stage of planning in some scenarios.
- If ACC is used as planning criterion, in some stage of planning WGD varies in a wide range over different scenarios. This means a high risk for planners.

Figures 5.12 (a)-(c) show that:

- If WGD is used as planning criterion, acceptable values of ACC will be achieved in different scenarios after four stages of planning.

Table 5.13 – Result of planning under SML criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	----	5	5	5	4	4	3	2.5	2.5
NC	----	112	57	42	69	62	75	101	87
MRP	----	12-29	5-20	11-9	10-18	8-12	20-24	5-21	13-17
CMP	----	71	138	172	99	208	76	92	55
SML:									
Sc1	2.6500	2.1243	1.7713	1.5122	1.4596	1.1537	1.1343	1.0610	1.0525
Sc2	2.4878	1.5974	1.5056	1.5500	1.2324	0.9499	0.8802	0.8813	0.8842
Sc3	2.6954	2.1552	1.8044	1.5542	1.5069	1.2029	1.1563	1.1015	1.1124
Sc4	2.7665	2.1001	1.8001	1.4835	1.4811	1.3079	1.2977	1.1959	1.1038
Sc5	2.5259	1.6444	1.5712	1.5977	1.3112	1.0877	0.8999	0.9132	0.9321
Sc6	2.5672	1.6357	1.5283	1.5459	1.2552	0.9679	0.8838	0.8713	0.8576
Sc7	2.7957	2.1139	1.8272	1.5195	1.5321	1.3564	1.3415	1.2601	1.1841
Sc8	2.5857	1.6936	1.6017	1.6092	1.3428	1.1112	0.9295	0.9463	0.9282
WGD:									
Sc1	2.0548	1.7943	1.6492	1.4426	1.4382	1.2508	1.2483	1.2139	1.2127
Sc2	1.8003	1.4268	1.3930	1.3875	1.1895	1.0203	0.9854	0.9841	0.9870
Sc3	2.0905	1.8179	1.6707	1.4665	1.4685	1.2777	1.2866	1.2608	1.2717
Sc4	2.0600	1.7347	1.6050	1.3898	1.4036	1.2614	1.2617	1.2159	1.1926
Sc5	1.8294	1.4645	1.4404	1.4371	1.2379	1.0852	1.0231	1.0288	1.0409
Sc6	1.7957	1.3964	1.3748	1.3668	1.1689	0.9799	0.9394	0.9263	0.9159
Sc7	2.0773	1.7460	1.6238	1.4111	1.4350	1.2881	1.3095	1.2712	1.2575
Sc8	1.8140	1.4386	1.4213	1.4085	1.2209	1.0444	0.9884	0.9887	0.9741
ACC:									
Sc1	2249.8	2079.2	2081.3	1804.4	1465.6	1129.8	1150.5	1141.0	1104.7
Sc2	1675.0	1447.7	1459.9	1194.0	1124.5	798.5	800.0	802.0	792.2
Sc3	2281.2	2116.0	2111.4	1829.1	1504.3	1167.6	1201.0	1225.1	1204.0
Sc4	2291.7	2081.2	2091.5	1621.9	1471.7	1152.0	1168.1	1170.0	1157.2
Sc5	1705.5	1504.5	1516.4	1252.4	1185.0	871.3	869.5	888.6	888.2
Sc6	1633.1	1413.0	1464.3	1178.8	1129.9	822.0	813.1	814.0	811.4
Sc7	2305.9	2099.7	2119.7	1648.1	1511.5	1190.7	1230.3	1264.5	1263.9
Sc8	1654.7	1458.9	1510.8	1218.5	1189.4	890.3	900.1	923.8	916.6

* Dimension of SV, SML, and WGD is $/MWhr, dimension of CMP is MW, and dimension of ACC is $/hr

* Sc1 = Scenario 1

Table 5.14 – Result of planning under WGD criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	----	5	5	5	4	4	3	3	3
NC	----	112	63	49	75	69	52	17	17
MRP	----	5-29	8-10	11-20	2-12	12-18	8-23	16-23	3-24
CMP	----	68	212	152	269	96	142	140	131
SML:									
Sc1	2.6500	2.1656	1.5909	1.3015	1.5278	0.5275	0.6475	0.6401	0.5362
Sc2	2.4878	1.5796	1.9032	1.5294	1.3071	0.9975	0.3931	0.3604	0.4604
Sc3	2.6954	2.2265	1.6062	1.3241	1.5520	0.6414	0.6709	0.6691	0.5105
Sc4	2.7665	2.1820	1.5451	1.3119	1.6758	0.7777	0.8933	0.6247	0.5575
Sc5	2.5259	1.6439	1.9252	1.5979	1.4609	1.1298	0.7173	0.6810	0.3259
Sc6	2.5672	1.5818	1.8857	1.5814	1.3582	1.0769	0.5661	0.4532	0.7467
Sc7	2.7957	2.2226	1.5718	1.3451	1.7015	0.8675	0.9134	0.7097	0.5380
Sc8	2.5857	1.6359	1.8727	1.6549	1.5162	1.2056	0.8589	0.8266	0.4413
WGD:									
Sc1	2.0548	1.7603	1.4735	1.2754	0.9646	0.4464	0.5122	0.5035	0.4375
Sc2	1.8003	1.3752	1.4483	1.2723	1.0367	0.8521	0.2917	0.2757	0.2979
Sc3	2.0905	1.7875	1.4812	1.2852	0.9836	0.4819	0.5183	0.5132	0.4269
Sc4	2.0600	1.7292	1.4029	1.2332	1.0361	0.5510	0.6184	0.4085	0.3480
Sc5	1.8294	1.4106	1.4764	1.3153	1.1113	0.9003	0.4377	0.4175	0.2308
Sc6	1.7957	1.3276	1.4393	1.2909	1.0727	0.9020	0.3858	0.3386	0.4341
Sc7	2.0773	1.7429	1.4175	1.2499	1.0536	0.5817	0.6246	0.4534	0.3228
Sc8	1.8140	1.3642	1.4301	1.3285	1.1492	0.9533	0.5165	0.5008	0.3142
ACC:									
Sc1	2249.8	2054.5	1374.4	1025.7	602.4	344.4	386.3	397.2	359.9
Sc2	1675.0	1442.8	965.2	806.1	530.0	430.5	256.1	241.4	247.8
Sc3	2281.2	2068.7	1388.1	1044.0	633.1	379.0	396.8	411.6	358.3
Sc4	2291.7	2071.2	1407.2	1082.7	632.3	409.3	448.2	406.8	366.5
Sc5	1705.5	1484.1	1004.6	866.5	611.5	485.9	368.2	342.2	231.5
Sc6	1633.1	1420.0	996.9	838.9	565.2	482.7	328.5	282.7	318.7
Sc7	2305.9	2078.9	1427.7	1107.7	662.4	441.9	459.7	440.2	364.8
Sc8	1654.7	1463.4	1000.1	883.2	648.4	538.5	437.5	390.5	282.1

* Dimension of SV, SML, and WGD is $/MWhr, dimension of CMP is MW, and dimension of ACC is $/hr

* Sc1 = Scenario 1

Table 5.15 – Result of planning under CC criterion

	Exist.net.	1st stage	2nd stage	3rd stage	4th stage	5th stage	6th stage	7th stage	8th stage
SV	----	5	5	5	5	5	5	3	3
NC	----	112	169	61	68	31	20	79	18
MRP	----	1-10	11-29	29-24	8-20	10-18	24-16	10-14	8-15
CMP	----	395	174	121	144	96	90	176	14
SML:									
Sc1	2.6500	3.3568	1.7473	1.6170	1.2524	1.0086	0.5153	0.3403	0.2794
Sc2	2.4878	3.8057	2.1318	2.1216	1.9326	1.5522	1.1309	0.6388	0.4956
Sc3	2.6954	3.3692	1.7838	1.3010	0.9862	0.6149	0.4513	0.3160	0.2639
Sc4	2.7665	3.4832	1.7451	1.5113	1.1799	0.8715	0.8265	0.7452	0.7500
Sc5	2.5259	3.8122	2.1759	2.0625	1.8767	1.4304	1.1347	0.5942	0.3981
Sc6	2.5672	3.9087	2.0383	1.8285	1.5698	1.2013	1.1860	0.7870	0.6807
Sc7	2.7957	3.4568	1.7947	1.2626	0.9862	0.6198	0.6574	0.4912	0.4430
Sc8	2.5857	3.8533	2.0509	1.6869	1.4501	1.1319	1.1278	0.6956	0.5399
WGD:									
Sc1	2.0548	1.9539	1.1448	1.0217	0.8264	0.6798	0.4775	0.3489	0.2922
Sc2	1.8003	2.3364	1.4973	1.3774	1.2880	1.1224	1.0276	0.6226	0.4846
Sc3	2.0905	1.9663	1.1675	0.8804	0.6788	0.4669	0.4172	0.3201	0.2649
Sc4	2.0600	1.9852	1.1433	1.0130	0.8467	0.7012	0.6703	0.5687	0.5548
Sc5	1.8294	2.3480	1.5523	1.3691	1.2832	1.0721	1.0174	0.5591	0.4066
Sc6	1.7957	2.3423	1.4763	1.2942	1.2172	1.0684	1.0539	0.7206	0.6000
Sc7	2.0773	1.9706	1.1720	0.8934	0.7304	0.5395	0.5754	0.4397	0.3968
Sc8	1.8140	2.3167	1.4833	1.2625	1.1945	1.0286	1.0196	0.6539	0.5187
ACC:									
Sc1	2249.8	1096.6	677.2	498.3	363.4	286.1	178.3	151.9	124.4
Sc2	1675.0	1148.6	751.7	591.1	516.4	413.2	311.3	222.2	151.2
Sc3	2281.2	1111.9	718.9	452.1	310.5	215.5	179.5	161.1	124.3
Sc4	2291.7	1123.1	728.0	528.5	398.9	321.6	284.2	266.4	229.4
Sc5	1705.5	1163.7	812.6	605.4	525.4	399.1	335.6	213.7	132.1
Sc6	1633.1	1144.6	787.3	577.4	513.9	388.6	348.2	292.9	209.1
Sc7	2305.9	1126.7	770.2	501.5	369.2	276.3	235.2	207.1	165.2
Sc8	1654.7	1144.8	803.8	599.5	533.4	388.0	335.0	261.9	175.7

* Dimension of SV, SML, and WGD is $/MWhr, dimension of CMP is MW, and dimension of ACC is $/hr

* Sc1 = Scenario 1

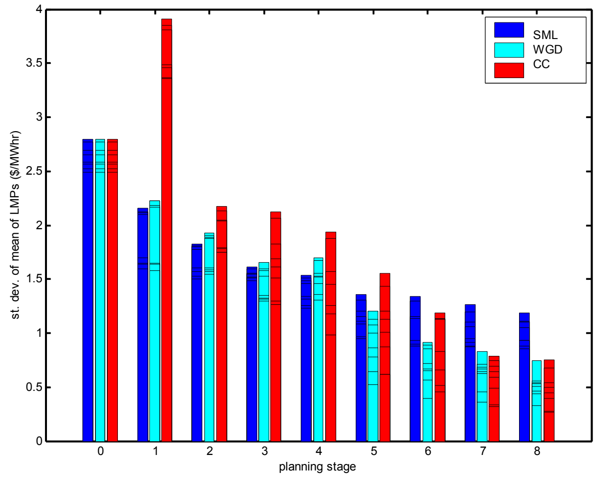


Fig. 5.10 (a) – Values of SML at different scenarios and different stages of planning (In each stage there are 3 bars. These three bars from left to right show the values of SML when SML, WGD, or ACC is used as planning criterion respectively. Over each bar there are eight signs which show the values of SML at different scenarios.)

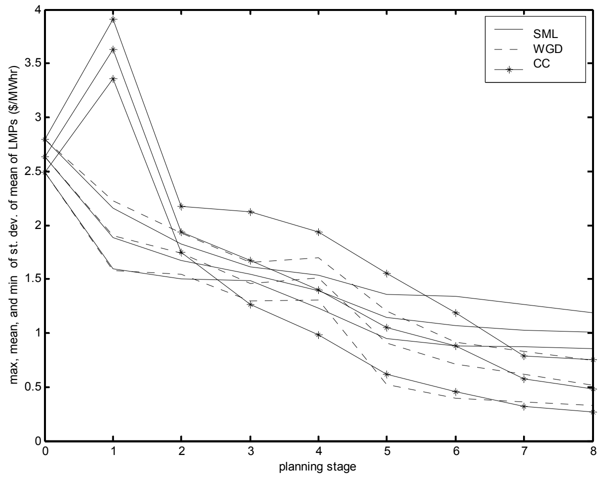


Fig. 5.10 (b) – Max, mean, and min of SML over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion.

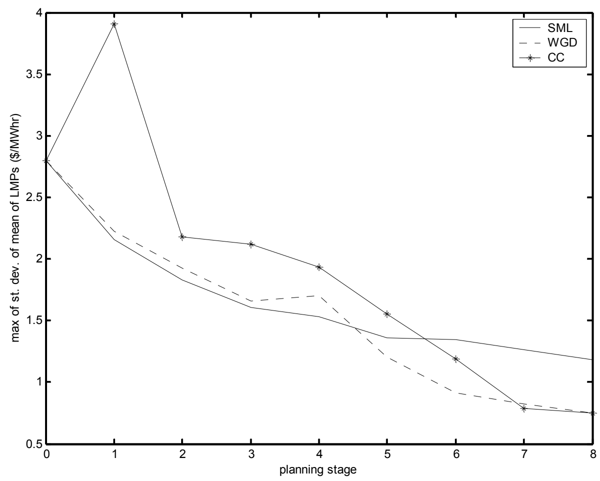


Fig. 5.10 (c) – Max of SML over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion.

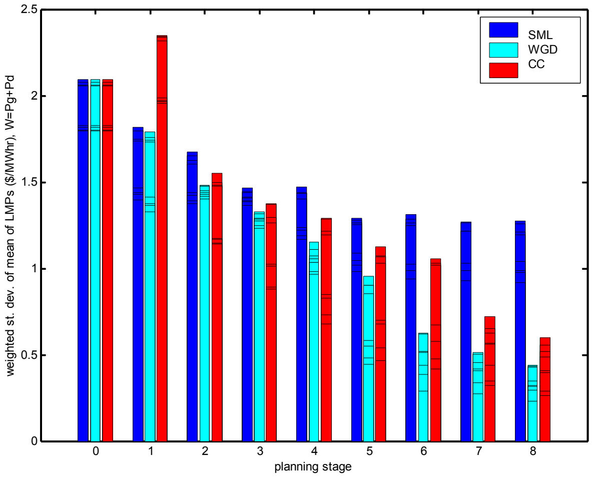


Fig. 5.11 (a) – Values of WGD at different scenarios and different stages of planning (In each stage there are 3 bars. These three bars from left to right show the values of WGD when SML, WGD, or ACC is used as planning criterion respectively. Over each bar there are eight signs which show the values of WGD at different scenarios.)

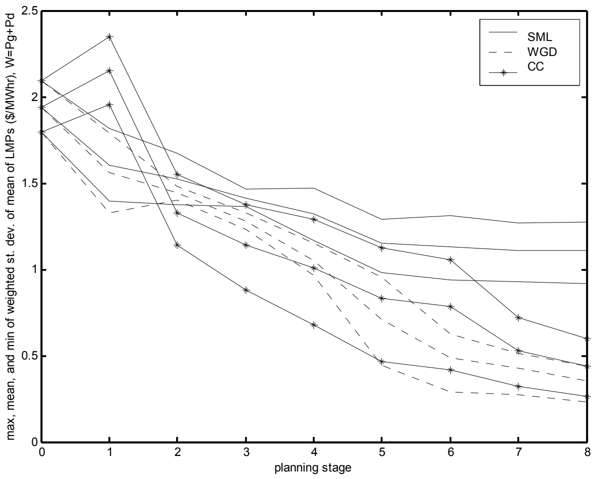


Fig. 5.11 (b) – Max, mean, and min of WGD over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion.

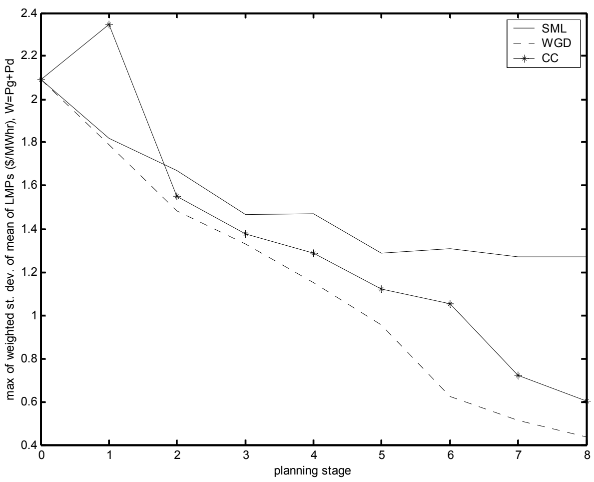


Fig. 5.11 (c) – Max of WGD over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion.

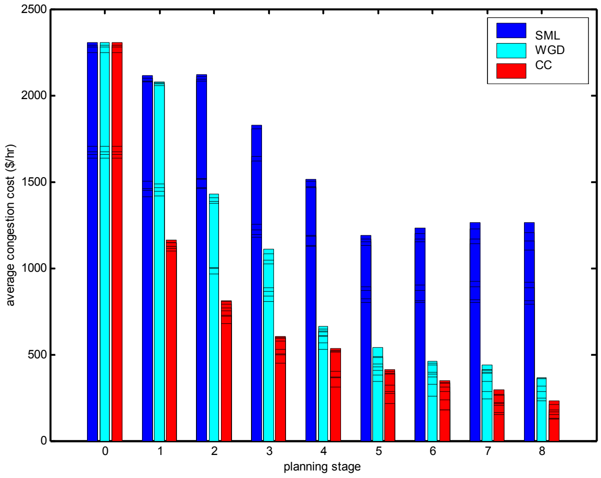


Fig. 5.12 (a) – Values of ACC at different scenarios and different stages of planning (In each stage there are 3 bars. These three bars from left to right show the values of ACC when SML, WGD, or ACC is used as planning criterion respectively. Over each bar there are eight signs which show the values of ACC at different scenarios.)

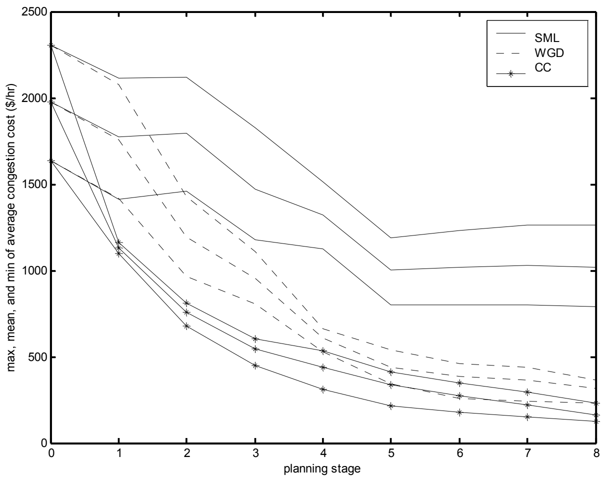


Fig. 5.12 (b) – Max, mean, and min of ACC over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion.

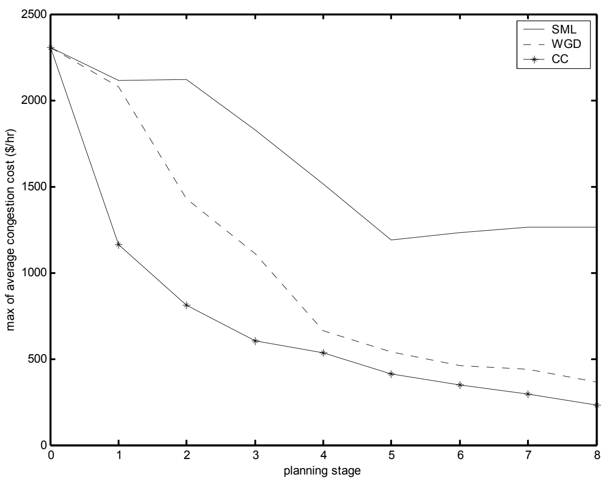


Fig. 5.12 (c) – Max of ACC over different scenarios at different stages of planning when SML, WGD, or ACC is used as planning criterion.

Finally the following conclusions can be drawn from this example:

- Transmission planning with ACC criterion tries to alleviate the congestion and transmission planning with SML, WG, WD, or WGD criterion tries to reduce the LMP differences. Since LMP differences appear due to congestion, as congestion is alleviated LMP differences vanish. Therefore, ACC is a more effective criterion than other criteria in single scenario cases.
- In multi scenario cases different lines may be congested in identified scenarios. That is, the cause of LMP differences is not the same in different scenarios. Hence, ACC criterion in multi scenario cases is not as effective as in single scenario cases in providing a flat price profile.
- WGD is an effective criterion for providing flat price profile and reducing congestion cost both in single and multi scenario cases. In this example WGD provides flatter price profile than ACC in multi scenario case.

5.3.3 Sensitivity Analysis

Determining the exact value of occurrence degree of a scenario is very difficult or impassible. Therefore, planners always worry about the impacts of error in estimating occurrence degrees of scenarios on the final result. To find out how much the final plan depends on the occurrence degrees of scenarios, a sensitivity analysis is done. The sensitivity analysis is performed for the first stage of planning of IEEE 30 bus test system which discussed in section 5.3.2. In section 5.3.2, it was assumed that the occurrence degrees of all scenarios are equal. For sensitivity analysis, it is assumed that:

$$\begin{cases} \upsilon^i = x \\ \upsilon^j = \dfrac{1-x}{7} \qquad j = 1,\ldots,8,\ j \neq i \end{cases} \tag{5.3}$$

with

υ^i occurrence degree of scenario i

Suppose $\upsilon^1 = x$, and $\upsilon^j = (1-x)/7$ for j = 1, …, 8, $j \neq i$. For sensitivity analysis x is changed from 0 to 1 step by step (step = 0.1). The values of x in which the selected plans by SML, WGD, or ACC changes are determined. The procedure is repeated for i = 2, …, 8. Table 5.16 shows the values of x in which the selected plan by SML, WGD, or ACC changes. For

Table 5.16 – Result of sensitivity analysis

Occurrence degrees of scenarios	Value of x in which selected plan changes	SML	WGD	ACC
$\upsilon^1 = x$, $\upsilon^j = (1 - x/7)$, $j = 2,...,8$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.29	14-29	“	“
	0.91	22-29	“	“
	1	“	“	“
$\upsilon^2 = x$, $\upsilon^j = (1 - x/7)$, $j = 1,...,8$, $j \neq 2$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.28	14-29	“	“
	0.63	“	“	1-21
	0.71	7-29	“	“
	1	“	“	“
$\upsilon^3 = x$, $\upsilon^j = (1 - x/7)$, $j = 1,...,8$, $j \neq 3$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.26	14-29	“	“
	0.41	“	“	“
	0.45	“	“	“
	0.59	“	14-29	“
	0.61	“	“	“
	0.73	13-29	22-29	“
	0.84	“	1-28	“
	1	“	“	“
$\upsilon^4 = x$, $\upsilon^j = (1 - x/7)$, $j = 1,...,8$, $j \neq 4$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.20	“	14-29	“
	0.24	14-29	“	“
	0.45	“	16-29	“
	0.64	16-29	“	“
	1	“	“	“
$\upsilon^5 = x$, $\upsilon^j = (1 - x/7)$, $j = 1,...,8$, $j \neq 5$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.30	14-29	“	“
	0.64	“	“	1-21
	0.76	7-29	“	“
	0.89	10-29	“	“
	1	“	“	“
$\upsilon^6 = x$, $\upsilon^j = (1 - x/7)$, $j = 1,...,7$, $j \neq 6$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.22	5-29	“	“
	0.45	7-29	“	“
	0.52	“	“	1-21
	0.57	“	“	“
	0.91	16-29	“	“
	0.95	“	“	“
	1	“	“	“
$\upsilon^7 = x$, $\upsilon^j = (1 - x/7)$, $j = 1,...,8$, $j \neq 7$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.18	“	14-29	“
	0.23	14-29	“	“
	0.26	13-29	“	“
	0.44	“	16-29	“
	0.55	“	“	“
	0.63	16-29	“	“
	1	“	“	“
$\upsilon^8 = x$, $\upsilon^j = (1 - x/7)$, $j = 1,...,7$ x changes from 0 to 1	0	12-29	5-29	1-10
	0.20	5-29	“	“
	0.38	7-29	“	“
	0.53	“	“	1-21
	0.61	“	“	“
	0.81	16-29	“	“
	0.86	“	10-29	“
	1	“	“	“

Example, if $i = 1$ at $x = 0$ ($\upsilon^1 = 0$, and $\upsilon^j = 0.143$ for $j = 2, \ldots, 8$) SML selects plan 12-29. If x increases at $x = 0.29$ ($\upsilon^1 = 0.29$, and $\upsilon^j = 0.101$ for $j = 2, \ldots, 8$) the selected plan by SML changes from 12-29 to 14-29.

The following results can be extracted from table 5.16:

- With the assumption of $\upsilon^1 = \upsilon^2 = \ldots = \upsilon^8 = 0.125$, SML selects line 12-29. If the occurrence degree of each scenario changes in the range of [0 0.2] while all other occurrence degrees remain equal, the result of planning under SML does not change.
- With the assumption of $\upsilon^1 = \upsilon^2 = \ldots = \upsilon^8 = 0.125$, WGD selects line 5-29. If the occurrence degree of each scenario changes in the range of [0 0.18] while all other occurrence degrees remain equal, the result of planning under WGD does not change.
- With the assumption of $\upsilon^1 = \upsilon^2 = \ldots = \upsilon^8 = 0.125$, ACC selects line 1-10. If the occurrence degree of each scenario changes in the range of [0 0.52] while all other occurrence degrees remain equal, the result of planning under ACC does not change.

Finally it is concluded that the presented approach is not very sensitive to the occurrence degrees of future scenarios. Criterion ACC is less sensitive than criteria SML and WGD to occurrence degrees of future scenarios.

6 Fuzzy Risk Assessment

In chapter 5 scenario technique was used to take into account non-random uncertainties. Minimax regret criterion was used for the risk assessment of the solutions. Scenario technique uses different criteria for selecting the final plan. But, each criterion has a shortcoming. In this chapter drawbacks of scenario technique criteria are pointed out. New criteria are presented for the scenario technique and fuzzy multi criteria decision making is used for the risk assessment of the solutions [69].

This chapter is organized as follows. Drawbacks of scenario technique criteria are pointed out in section 6.1. New criteria for risk assessment are presented in section 6.2. In section 6.3 the presented model for transmission expansion planning with fuzzy risk assessment is overviewed. The model is described in detail in section 6.4. In section 6.5 the presented approach is applied to IEEE 30 bus test system and the results are compared with conventional risk assessment to demonstrate that fuzzy risk assessment overcomes the shortcomings of conventional risk assessment methods.

6.1 Shortcomings of Scenario Technique Criteria

Scenario technique uses different criteria for selecting the final plan (refer to 2.1.1.3). But, each criterion has a shortcoming. Expected cost and Laplace criteria are not valid since the scenarios are not repeatable. Minimax regret and β-robustness criteria are used for very important decisions, where surviving under an unlikely but catastrophic scenario is needed. In addition these criteria are relative. Von Neumann-Morgenstern and Hurwicz criteria are extremely pessimistic or extremely optimistic. Robustness criterion is very crisp and hence is not logical always. Minimax regret, robustness and expected cost are the most important criteria and are used frequently for selecting the final plan. Let us to describe shortcomings of these three criteria in detail:

Minimax regret: this criterion is used for very important decisions, where surviving under an unlikely but catastrophic scenario is needed. In addition this criterion is not absolute i.e. if an unrealistic plan is added to the set of expansion candidates; it will contribute to the selection of inferior plans. To clear the relativeness drawback of minimax regret criterion, consider the simple example of table 6.1 with three scenarios and two plans. The scenarios have equal degrees of occurrence. Cost of expansion plans in different scenarios is given in table 6.1. Optimal plan of each scenario is specified by an arrow in this table. Table 6.2 shows the regrets of expansion plans in different scenarios. Maximum regret of each plan is specified by an arrow in this table. As shown in this table, plan 1 has the minimax regret. Now suppose plan 3 is added to the set of solutions. Cost of plan 3 is given in table 6.3. Table 6.4 shows the regrets after adding plan 3 to the set of solutions. This table shows that, if plan 3 is added to the set of solutions, regrets of plan 1 and 2 in scenario C change since the optimal plan of scenario C changes. Consequently, maximum regret of plans 1 and 2 change. This cause minmax regret transfer from plan 1 to plan 2. As you see, after adding plan 3, minimax regret criterion changes its opinion and selects plan 2 as the final plan. As it is shown in table 6.4, regrets of plan 1 in scenarios A and B are smaller than regrets of plan 2 noticeably. In scenario C regret of plan 1 is greater than regret of plan 2 but the difference is negligible. Therefore, plan 2 is riskier than plan 1. In spite of this matter, plan 2 is selected by minimax regret criterion as the final plan. This example shows how unrealistic plans contribute to the selection of inferior plans. Note that plan 3 is an unrealistic plan since in scenario C in spite of

Table 6.1- Cost of plans 1, and 2 in scenarios A, B, and C

	Scenario A	Scenario B	Scenario C
Plan 1	10.00	10.10	10.50
Plan 2	12.00	12.60	10.45

Table 6.2- Regrets of plans 1, 2 before adding plan 3

	Scenario A	Scenario B	Scenario C	Max regret
Plan 1	0	0	0.05	0.05
Plan 2	2.00	2.50	0	2.50

Table 6.3- Cost of plans 1, 2, and 3 in scenarios A, B, and C

	Scenario A	Scenario B	Scenario C
Plan 1	10.00	10.10	10.50
Plan 2	12.00	12.60	10.45
Plan 3	12.61	11.20	7.85

Table 6.4- Regrets of plans after adding plan 3

	Scenario A	Scenario B	Scenario C	Max regret
Plan 1	0	0	2.65	2.65
Plan 2	2.00	2.50	2.60	2.60
Plan 3	2.61	1.10	0	2.61

other scenarios cost of plan 3 is noticeably smaller than cost of other plans. Although minimax regret criterion has shortcomings, maximum regret is an important parameter for selecting the final plan. Therefore, we use maximum regret as a criterion in fuzzy multi criteria decision making for selection the final plan.

Robustness**:** plan *k* is robust in scenario *l* if its regret is zero in scenario *l*. Plan *k* is robust if it is robust in all scenarios. If regret of a plan in a scenario is very small, according to this criterion this plan is not robust in this scenario. For example consider plan 1 in table 6.2, the regret of this plan in scenario C is 0.05 which is negligible in comparison with other regrets. But according to definition of robustness this plan is not robust in scenario C. If a plan is robust in all scenarios except one scenario in which its regret is a very small, according to this criterion this plan is not robust. Consider table 6.2 again, plan 1 is robust in scenarios A and B and its regret in scenario C is negligible, but it is not robust. According to the definition of robustness none of plans 1 and 2 are robust. This criterion can not judge about plan 1 and 2. Therefore, this criterion is very crisp and hence is not logical always. In fact this criterion has two drawbacks:

a) It can not judge about the regret values greater than zero.
b) It can not judge about plans which are not robust in all scenarios.

To overcome these drawbacks, new criteria are defined in next section.

Expected cost**:** since scenarios are not repeatable, the basic assumption of probability does not hold and therefore this criterion is not valid for non-random uncertainties. Therefore expected cost of a plan over different scenarios can not be interpreted as expected value of the cost of this plan. Since only one scenario will occur in the future and will not be repeated. Expected cost for non-random scenarios can be interpreted as the average of costs over different scenarios. Although minimum of average cost is not solely a good criterion for selecting the final plan, it is an important parameter for selecting the final plan. We will use average regret as a criterion in fuzzy multi criteria decision making.

6.2 New Criteria for Risk Assessment

To overcome the drawbacks of robustness criterion, the following criteria are defined:

Definition:

Plan *k* is robust of order *m* in scenario *l* if its regret in scenario *l* is in the range of $[(m\text{-}1)\zeta \ \ m\zeta)$. Where ζ is a percentage of maximum regret over all plans and scenarios (e.g.

2 or 5 percent of maximum regret). The value of ζ depends on the variations of regrets.

Definition:

Degree of robustness of order *m* of plan *k* is equal to the number of scenarios in which plan *k* is robust of order *m*.

Degree of robustness of order *m* considers both values of regrets and number of scenarios in which plans are robust of order *m*. The following decision criteria are used to select the final plan using fuzzy multi criteria decision making:

- maximum regret,
- average regret,
- degree of robustness of order one,
- degree of robustness of order two,
- degree of robustness of order three,
- degree of robustness of order four, and
- degree of robustness of order five.

6.3 Model Overview

Transmission expansion planning approach with fuzzy risk assessment can be precised in the following steps:

1) Identifying the set of possible strategic scenarios (refer to 5.2.1)
2) Suggesting candidates for transmission expansion by analyzing electric market (refer to 5.2.2)
3) Computing the market based criteria for each plan in each scenario (refer to 5.2.3)
4) Selecting the final plan using fuzzy risk assessment (refer to 6.4.1)
5) Computing the capacity of selected expansion plan (refer to 5.2.5)

6.4 Model in Detail

This approach is the same as the presented approach in chapter 5, except step 4. In this step the final plan is selected using fuzzy risk assessment instead of minimax regret criterion. Fuzzy risk assessment method is described in the following subsections.

6.4.1 Fuzzy Risk Assessment

Consider a network and assume we want to design a transmission expansion plan for a specified planning horizon. Suppose steps 1-3 have been done and we are in the step 4 of transmission expansion planning. In step 3, a market based criterion, say weighted standard deviation of mean of LMP, has been computed for measuring the goodness of each expansion plan in each scenario. Regrets are computed considering the occurrence degrees of future scenarios. Now there is a table of regrets and the desire is to select the final plan. In this section fuzzy multi criteria decision making is used for selecting the final plan [27]. In this method a fuzzy appropriateness index is defined for selecting the final plan. The fuzzy appropriateness index is computed by aggregation of importance degrees of decision criteria and appropriateness degrees of expansion plans versus decision criteria.

6.4.1.1 Importance Weights of Decision Criteria

The presented decision criteria for risk assessment do not have the same degree of importance. To represent the importance weights of decision criteria, the following linguistic variables are used:

$$W = \{\text{VL, L, M, H, VH}\}$$

where VL, L, M, H, and VH are abbreviations of very low, low, medium, high, and very high respectively. Degree of robustness of order 1 is very important in decision making. Maximum and average of regret are also important. Degree of robustness of order 5 has the lowest importance in decision making. Table 6.5 shows the selected importance weights for the decision criteria. A triangular fuzzy number is assigned to each linguistic variable. Table 6.6 shows the triangular fuzzy numbers.

6.4.1.2 Appropriateness Degrees of Expansion Plans Versus Decision Criteria

Suppose C_i^k for i=1, …7 is the criterion which is used for measuring maximum regret (i=1), average regret (i=2), degree of robustness of order 1 (i=3), …, and degree of robustness of

Table 6.5- Importance degrees of decision criteria

Criterion	MR	AR	R1	R2	R3	R4	R5
Importance Weight	H	H	VH	H	M	L	VL

Table 6.6- Triangular fuzzy numbers corresponding to linguistic variables

Linguistic Variable	VL	L	M	VH	H
Fuzzy Number	(0, 0, 1/4)	(0, 1/4, 2/4)	(1/4, 2/4, 3/4)	(2/4, 3/4, 1)	(3/4, 1, 1)

order 5 (i=7) of plan k. Smaller maximum regret and smaller average regret indicate better situation. Therefore, inverse of these criteria are used to measure the appropriateness degrees of expansion plans versus maximum and average regret. Greater degree of robustness of order m for m=1, …, 5 indicate better situation. Therefore, these criteria are used to measure the appropriateness degrees of expansion plans versus degree of robustness of order m. Suppose A_i^k is the appropriateness degree of plan k versus decision criterion i, then:

$$A_i^k = 1 / C_i^k \qquad \text{for } i=1, 2 \tag{6.1}$$

$$A_i^k = C_i^k \qquad \text{for } i=3, \ldots, 7 \tag{6.2}$$

For aggregating the appropriateness degrees of expansion plans versus different decision criteria, the appropriateness degrees must be comparable versus different decision criteria. Therefore, A_i^k is normalized on its maximum value over different expansion plans:

$$N_i^k = A_i^k / \max_k (A_i^k) \tag{6.3}$$

with:

N_i^k normalized appropriateness degree of plan k versus decision criterion i

6.4.1.3 Fuzzy Appropriateness Index

Let $W_i \in W$ be the importance weight of decision criterion i. Appropriateness degree of plan k versus combination of all decision criteria is equal to weighted mean of N_i^k, i.e.:

$$F_{ap}^k = \frac{1}{N_{dc}} \left[(W_1 \otimes N_1^k) \oplus (W_2 \otimes N_2^k) \oplus \ldots \oplus (W_{N_c} \otimes N_{N_{dc}}^k) \right] \tag{6.4}$$

with:

F_{ap}^k fuzzy appropriateness index of plan k versus combination of all decision criteria

N_{dc} number of decision criteria

$\oplus$ fuzzy addition operator

$\otimes$ fuzzy multiplication operators

Fuzzy arithmetic operations are defined using α-cuts of fuzzy intervals [74]-[75].

6.4.1.4 Selecting the Final Plan

The expansion plan that has the greatest fuzzy appropriateness index is selected as the final plan. To find the plan which has maximum fuzzy appropriateness index, fuzzy appropriateness indices must be ranked. Many methods were presented for ranking fuzzy numbers. Here, we use convex combination of left and right integral values [27], [75]-[76], centroid indices [77], and extended centroid index [77] for ranking fuzzy numbers.

6.5 Case Study: IEEE 30 Bus Test System

The proposed approach is applied to IEEE 30 bus test system [62], [64]. Figure 5.1 shows the single line diagram of IEEE 30 bus test system. Data of generators, loads, and transmission lines are given in tables 5.2-5.4. To demonstrate that the fuzzy risk assessment overcomes the shortcomings of conventional risk assessment method, four different cases are considered.

***Case 1*:** Consider the IEEE 30 bus test system with eight different scenarios which were identified in section 5.3.2. It is assumed that all scenarios have the same degree of occurrence. In section 5.3.2, PDFs of LMPs were computed for the peak load of planning horizon of the existing network at different scenario. If between each two buses that have average LMP difference greater than \$5/MWhr a new transmission line is suggested, we have 113 decision alternatives (candidates) including alternative "do nothing". Standard deviation of mean of LMP weighted with mean of sum of generation power and load (WGD) is used for measuring the goodness of expansion plans. The following approaches are used for selecting the final plan:

- Conventional risk assessment with minimax regret criterion (MMR),
- Conventional risk assessment with minimum expected cost criterion (MEC),
- Fuzzy risk assessment with the following methods for ranking fuzzy numbers:
  - x of centroid point (XC),
  - distance of centroid point from zero (DC),
  - distance of extended centroid point from zero (DEC),
  - convex combination of right and left integral values with α=0 (I0), α=0.5 (I5), and α=1 (I1).

Tables 6.7 and 6.8 show WGD and regrets for plans 1-28, 5-29, 14-29, 16-29 in \$/MWhr. In this case all above approaches select plan 5-29 as the final plan. As it is shown in table 6.8, this plan is robust in five scenarios. It also has the minimax regret and minimum expected cost.

Table 6.7- WGD of plans 1-28, 5-29, 14-29, 16-29 in case 1

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	1.7626	1.4640	1.7806	1.7473	1.4936	1.5171	1.7602	1.5503
Plan 5-29	1.7603	1.3752	1.7875	1.7292	1.4106	1.3276	1.7429	1.3642
Plan 14-29	1.7628	1.4052	1.7861	1.7273	1.4360	1.3969	1.7364	1.4322
Plan 16-29	1.8583	1.5907	1.8877	1.6876	1.6330	1.3294	1.6947	1.3676

Table 6.8- Regrets of plans 1-28, 5-29, 14-29, 16-29 in case 1

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	0.0022	0.0887	0	0.0597	0.0830	0.1895	0.0654	0.1861
Plan 5-29	0	0	0.0070	0.0416	0	0	0.0482	0
Plan 14-29	0.0025	0.0299	0.0056	0.0397	0.0255	0.0693	0.0417	0.0681
Plan 16-29	0.0979	0.2154	0.1072	0	0.2224	0.0018	0	0.0035

***Case 2*:** Suppose another plan (plan 114) is added to the set of expansion candidates. WGD of plan 114 in different scenarios is given in table 6.9. In this case, minimax regret selects plan 114 while other methods still select plan 5-29 as the final plan. Regrets of plans 1-28, 5-29, 14-29, 16-29 and plan 114 are given in table 6.10. This table shows that regrets of plan 114 are greater than regrets of plan 5-29 in all scenarios except scenario 7. Even in this scenario, the difference is negligible. Hence plan 114 is riskier than plan 5-29. This example shows that conventional risk assessment with minimax regret criterion selects riskier plan than other approaches.

Table 6.9- WGD of plans 1-28, 5-29, 14-29, 16-29, and plan 114 in case 2

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	1.7626	1.4640	1.7806	1.7473	1.4936	1.5171	1.7602	1.5503
Plan 5-29	1.7603	1.3752	1.7875	1.7292	1.4106	1.3276	1.7429	1.3642
Plan 14-29	1.7628	1.4052	1.7861	1.7273	1.4360	1.3969	1.7364	1.4322
Plan 16-29	1.8583	1.5907	1.8877	1.6876	1.6330	1.3294	1.6947	1.3676
Plan 114	1.7700	1.4000	1.8000	1.7300	1.4500	1.3700	1.7300	1.4000

Table 6.10- Regrets of plans 1-28, 5-29, 14-29, 16-29 and plan 114 in case 2

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	0.0022	0.0887	0	0.0597	0.0830	0.1895	0.0654	0.1861
Plan 5-29	0	0	0.0070	0.0416	0	0	0.0482	0
Plan 14-29	0.0025	0.0299	0.0056	0.0397	0.0255	0.0693	0.0417	0.0681
Plan 16-29	0.0979	0.2154	0.1072	0	0.2224	0.0018	0	0.0035
Plan 114	0.0097	0.0248	0.0194	0.0424	0.0394	0.0424	0.0353	0.0358

***Case 3*:** Now suppose WGD of plan 114 be as table 6.11. After adding plan 114 to the set of expansion plans, minimax regret criterion selects plan 14-29 while other methods still select

plan 5-29 as the final plan. Regrets of plans 1-28, 5-29, 14-29, 16-29, and plan 114 are given in table 6.12. It is seen that in scenarios 1, 2, 5, 6, and 8 regrets of plan 14-29 are greater than regrets of plan 5-29. Differences between regrets in scenarios 6 and 8 are noticeable. In scenarios 3, 4, and 7 regrets of plan 14-29 are smaller than regrets of plan 5-29 but differences between regrets are negligible. Hence plan 14-29 is riskier than plan 5-29. In this case addition of plan 114 to the set of expansion plans affects the decision of minimax regret criterion and makes it to select an inferior plan. Addition of plan 114 does not affect the decision of fuzzy risk assessment.

Table 6.11- WGD of plans 1-28, 5-29, 14-29, 16-29, and plan 114 in case 3

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	1.7626	1.4640	1.7806	1.7473	1.4936	1.5171	1.7602	1.5503
Plan 5-29	1.7603	1.3752	1.7875	1.7292	1.4106	1.3276	1.7429	1.3642
Plan 14-29	1.7628	1.4052	1.7861	1.7273	1.4360	1.3969	1.7364	1.4322
Plan 16-29	1.8583	1.5907	1.8877	1.6876	1.6330	1.3294	1.6947	1.3676
Plan 114	1.8600	1.6000	1.8900	1.6900	1.7500	1.5200	1.6700	1.5600

Table 6.12- Regrets of plans 1-28, 5-29, 14-29, 16-29 and plan 114 in case 3

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	0.0022	0.0887	0	0.0597	0.0830	0.1895	0.0902	0.1861
Plan 5-29	0	0	0.0070	0.0416	0	0	0.0729	0
Plan 14-29	0.0025	0.0299	0.0056	0.0397	0.0255	0.0693	0.0664	0.0681
Plan 16-29	0.0979	0.2154	0.1072	0	0.2224	0.0018	0.0247	0.0035
Plan 114	0.0997	0.2248	0.1094	0.0024	0.3394	0.1924	0	0.1958

Case 4**:** Suppose WGD of plan 114 is as table 6.13. The expected cost of plans 5-29 and plan 114 are equal to \$1.5622/MWhr and \$1.5625/MWhr respectively. After adding plan 114 to the set of expansion plans, expected cost criterion selects plan 5-29 while other methods select plan 114 as the final plan. Regrets of plans 1-28, 5-29, 14-29, 16-29, and plan 114 are given in table 6.14. This table shows that regrets of plan 114 are in the same range in all scenarios but regrets of plan 5-29 are not in the same range. Note that regret of plan 5-29 in scenario 7 is three times greater than maximum regret of plan 114. Hence, if we select plan 5-29 and scenario 7 occurs we have a great regret. Thus, solution of fuzzy risk assessment is more logical than expected cost criterion. Table 6.15 shows the selected plans by different method in cases 1-4.

Table 6.13 WGD of plans 1-28, 5-29, 14-29, 16-29, and plan 114 in case 4

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	1.7626	1.4640	1.7806	1.7473	1.4936	1.5171	1.7602	1.5503
Plan 5-29	1.7603	1.3752	1.7875	1.7292	1.4106	1.3276	1.7429	1.3642
Plan 14-29	1.7628	1.4052	1.7861	1.7273	1.4360	1.3969	1.7364	1.4322
Plan 16-29	1.8583	1.5907	1.8877	1.6876	1.6330	1.3294	1.6947	1.3676
Plan 114	1.7700	1.4000	1.8000	1.7000	1.4400	1.3500	1.6500	1.3900

Table 6.14 Regrets of plans 1-28, 5-29, 14-29, 16-29 and plan 114 in case 4

	Scen. 1	Scen. 2	Scen. 3	Scen. 4	Scen. 5	Scen. 6	Scen. 7	Scen. 8
Plan 1-28	0.0022	0.0887	0	0.0597	0.0830	0.1895	0.1102	0.1861
Plan 5-29	0	0	0.0070	0.0416	0	0	0.0929	0
Plan 14-29	0.0025	0.0299	0.0056	0.0397	0.0255	0.0693	0.0864	0.0681
Plan 16-29	0.0979	0.2154	0.1072	0	0.2224	0.0018	0.0447	0.0035
Plan 114	0.0097	0.0248	0.0194	0.0124	0.0294	0.0224	0	0.0258

Table 6.15- Selected plans by different approaches in different cases

	MMR	MEC	I0	I5	I1	XC	DC	DEC
Case 1	5-29	5-29	5-29	5-29	5-29	5-29	5-29	5-29
Case 2	Plan 114	5-29	5-29	5-29	5-29	5-29	5-29	5-29
Case 3	14-29	5-29	5-29	5-29	5-29	5-29	5-29	5-29
Case 4	Plan 114	5-29	Plan 114	Plan 114	Plan 114	Plan 114	Plan 114	Plan 114

7 Stakeholders' Desires

Restructuring and deregulation have unbundled the roles within network stakeholders. In unbundled power systems stakeholders have different interests and expectations from the performance and expansion of the system. This chapter presents a new market based approach for transmission expansion planning with consideration given to the stakeholders' desires using fuzzy decision making [70]-[71]. The approach takes into account the desires of all stakeholders in transmission expansion planning.

This chapter is organized as follows. Power system stakeholders and stakeholders' desires are discussed in section 7.1. Market based criteria are presented for measuring stakeholders' desires in section 7.2. The presented model for transmission expansion planning with consideration given to stakeholders' desires is overviewed in section 7.3. The model is described in detail in section 7.4. In section 7.5, the presented approach is applied to IEEE 30 bus test system.

7.1 Power System Stakeholders

In a deregulated environment stakeholders are grouped into four main categories according to their roles [2]:

- Managers of the transmission network including transmission administrator, system operator, network owners, measurement and metering administrator.
- Users of the transmission network for energy trading including demand customers and power producers.
- Facilitators of the energy trading including market operator, energy retailers, energy traders, and power brokers.
- Statutory authorities including electricity regulator and other public authorities.

The stakeholders who have interests in transmission expansion and exert driving force for network development are demand customers, power producers, network owner(s), system operator, and regulator [2]. The desires of these stakeholders must be considered in transmission expansion planning. The desires of these stakeholders are described in bellow.

Demand customers: from the viewpoint of demand customers the desired transmission plan is the plan that reduces transmission constraints between loads and cheap generations. They are also seeking the plan which provides low network charge and high network reliability.

Power producers**:** from the viewpoint of power producers the plan that removes the transmission constraints for dispatching generators and provides a competitive environment is the best plan. Network reliability is also important for power producer to sell their power continuously.

System operator**:** system operator seeks the plan which provides a high flexibility in system operation. Network reliability, congestion cost and transmission losses are also important for system operator.

Network owners**:** the objective of network owners is to maximize their revenue. Therefore they seek the minimum cost and maximum income plan.

Regulator**:** from the viewpoint of regulator the desired plan is the plan which encourages competition, provides equity for all parties seeking network access, has high network reliability, low operation cost and low environmental impacts.

7.2 Measuring the Stakeholders' Desires

Transmission planner must consider the desires of all stakeholders. The stakeholder desires can be sought in: competition, reliability, flexibility in operation, network charge and environmental impacts [2]. Under competition, we have equity among all customers, minimum operation cost, and minimum congestion cost. Transmission planners need some criteria to measure the stakeholders' desires. The following market based criteria can be used for measuring the stakeholders' desires.

Competition**:** the market based criteria which were presented in chapter 4 including weighted standard deviation of mean of LMP and average congestion cost can be used to measure how much an expansion plan promotes the competition.

Reliability**:** average load curtailment cost is used to measure the network reliability.

Flexibility: average load curtailment cost can also be used to measure the flexibility of network operation. The network is more flexible to operate if there is no congested line. If expansion planning reduces the number of congested lines, flexibility of network operation will be increased. Therefore, number of congested lines can be used as a criterion for measuring the flexibility of network operation. Here, number of lines with average power greater than 0.9 of their limits multiplied by average load curtailment cost is used to measure the flexibility of network operation.

Network charge: annual investment cost of expansion plans divided by sum of network loads is used to measure how much an expansion plan increases the network charge.

Environmental impacts: cost of compensating the environmental impacts is used to measure the environmental impacts of each expansion plan.

7.3 Model Overview

Consider a network and assume we want to design a transmission expansion plan for a specified planning horizon. Non-random uncertainties are not considered in this approach and hence there is only one scenario. The approach consists of the following steps:

1) Determining the set of expansion plans by market analysing (refer to 5.2.2)
2) Measuring the goodness of expansion plans based on stakeholders' desires (refer to 7.4.1)
3) Selecting the final plan (refer to 7.4.2)
4) Computing the capacity of selected expansion plan (refer to 5.2.5)

7.4 Model in Detail

The first step of planning i.e. "Determining the set of expansion plans" is the same as chapters 5 and 6. In chapter 5 and 6 we used the market based criteria, which presented in chapter 4, to measure how much an expansion plan increases the competition. In this chapter in addition the competition, other desires of stakeholders are taken into account. Therefore, an appropriateness index must be defined to measure the goodness of expansion plans versus combination of all stakeholders' desires. Because of the vagueness in importance degrees of stakeholders and their desires a fuzzy appropriateness index is defined. Steps 2 and 3 are described in the following subsections. Step 4 is the same as chapters 5 and 6.

7.4.1 Measuring the Goodness of Expansion Plans

In this section a fuzzy appropriateness index is defined for measuring the goodness of expansion plans. The appropriateness index is defined by aggregating:

- importance weights of stakeholders in decision making,
- importance degrees of stakeholders' desires from the viewpoint of different stakeholders,
- and appropriateness degrees of expansion plans versus different stakeholders' desires.

7.4.1.1 Importance Degrees of Stakeholders and Their Desires

Stakeholders do not have the same degree of importance in transmission expansion decision making. Therefore a degree of importance must be assigned to each stakeholder. Also, they have different degrees of interest in each desire. Hence, a degree of importance must be also assigned to each desire from the viewpoint of each stakeholder. Because of the vagueness in importance degrees, fuzzy numbers are used to represent these importance degrees. To represent the importance weights of each stakeholder in decision making, the following linguistic variables are used:

$$X = \{\text{VL, L, M, H, VH}\}$$

where VL, L, M, H, and VH are abbreviations of very low, low, medium, high, and very high respectively. To represent the importance degree of each desire from the viewpoint of each stakeholder, the following linguistic variables are used:

$$Y = \{\text{U, LI, PI, I, VI}\}$$

where U, LI, PI, I, and VI are abbreviations of unimportant, little important, pretty important, important, and very important respectively. A triangular fuzzy number is assigned to each element of above sets. Table 7.1 shows the triangular fuzzy numbers. A survey was done in order to determine the importance weights of stakeholders and importance degrees of stakeholders' desires from the viewpoint of different stakeholders. A questionnaire was sent to a number of professors and Ph.D. students who are involved in transmission planning research. A compromise among the answers is used for decision making. Tables 7.2 and 7.3 show these importance weights.

Table 7.1- Triangular fuzzy numbers corresponding to linguistic variables

Linguistic Variable	VL / U	L / LI	M / PI	H / I	VH / VI
Fuzzy Number	(0, 0, 0.25)	(0, 0.25, 0.5)	(0.25, 0.5, 0.75)	(0.5, 0.75, 1)	(0.75, 1, 1)

Table 7.2- Importance weights of stakeholders in decision making

Stakeholders	Power Producers	Demand Customers	System Operator	Network Owners	Regulator
Weight of importance	L	H	L	M	M

Table 7.3- Importance degrees of stakeholders' desires from viewpoint of stakeholders

	Competition	Reliability	Flexibility	Network Charge	Environmental Impacts
Power Producers	VI	I	PI	PI	U
Demand Customers	VI	VI	I	I	U
System operator	LI	VI	VI	LI	U
Network Owners	U	PI	LI	VI	LI
Regulator.	VI	VI	I	I	VI

7.4.1.2 Appropriateness Degrees of Expansion Plans Versus Stakeholders' Desires

Suppose C_i^k for i=1, .., 5 is the criterion which is used for measuring competition (i=1), reliability (i=2), operation flexibility (i=3), network charge (i=4), and environmental impacts (i=5) of plan k. Smaller values of all these criteria indicate better conditions. Hence, inverse of these criteria are used to measure the appropriateness degrees of expansion plans:

$$\mathcal{A}_i^k = 1/C_i^k \qquad \text{for } i=1, \ldots, N_{sd} \tag{7.1}$$

with:

$\mathcal{A}_i^k$ appropriateness degree of plan k versus criterion i

N_{sd} number of stakeholders' desires

For aggregating the appropriateness degrees of expansion plans versus different decision criteria, the appropriateness degrees must be comparable versus different decision criteria. Therefore, $\mathcal{A}_i^k$ is normalized on its maximum value over different expansion plans.

$$\mathcal{N}_i^k = \mathcal{A}_i^k / \max_k(\mathcal{A}_i^k) \qquad \text{for } i=1, 2, \ldots, N_{sd} \tag{7.2}$$

with:

$\mathcal{N}_i^k$ normalized appropriateness degree of plan k versus decision criterion i

7.4.1.3 Fuzzy Appropriateness Index

Let $X_j \in X$ is the importance weight of stakeholder j in decision making and Y_{ij} is the importance degree of desire i from the viewpoint of stakeholder j. The importance degree of desire i from the viewpoint of transmission planners is equal to the weighted mean of Y_{ij} i.e.:

$$U_i = \frac{1}{N_{st}}\left[(X_1 \otimes Y_{i1}) \oplus (X_2 \otimes Y_{i2}) \oplus \ldots \oplus (X_{N_{st}} \otimes Y_{iN_{st}})\right] \qquad \text{for } i=1,\ldots, N_{sd} \tag{7.3}$$

with:

U_i importance degree of desire i from the viewpoint of transmission planners

N_{st} number of stakeholder groups

Fuzzy arithmetic operations are defined using α-cuts of fuzzy intervals [74]-[75]. If X_j and Y_{ij} are substituted by triangular fuzzy numbers i.e. $X_j=(a_j, b_j, c_j)$ and $Y_{ij}=(o_{ij}, p_{ij}, q_{ij})$, U_i is approximated by (l_i, m_i, n_i) [27].
where:

$$l_i = \frac{1}{N_{st}}\sum_{j=1}^{N_{st}} o_{ij}\, a_j\,, \qquad i=1,\ldots, N_{sd} \tag{7.4}$$

$$m_i = \frac{1}{N_{st}}\sum_{j=1}^{N_{st}} p_{ij}\, b_j\,, \qquad i=1,\ldots, N_{sd} \tag{7.5}$$

$$n_i = \frac{1}{N_{st}}\sum_{j=1}^{N_{st}} q_{ij}\, c_j\,, \qquad i=1,\ldots, N_{sd} \tag{7.6}$$

Appropriateness degree of plan k versus combination of all decision criteria is equal to weighted mean of $\mathcal{N}_i^k$, i.e.:

$$\mathcal{F}_{ap}^k = \frac{1}{N_{sd}}\left[(U_1 \otimes \mathcal{N}_1^k) \oplus (U_2 \otimes \mathcal{N}_2^k) \oplus \ldots \oplus (U_{N_d} \otimes \mathcal{N}_{N_{sd}}^k)\right] \qquad \text{for } k=1, \ldots, N_p \tag{7.7}$$

with:

$\mathcal{F}_{ap}^k$ fuzzy appropriateness index of plan k versus combination of all decision criteria with considering importance degree of stakeholders in decision making

N_p number of expansion plans

7.4.2 Selecting the Final Plan

The expansion plan which has the greatest fuzzy appropriateness index is the optimal plan. As chapter 6, convex combination of left and right integral value [27], [75]-[76], centroid indices [77], and extended centroid index [77] are used for ranking fuzzy numbers.

7.5 Case Study: IEEE 30 Bus Test System

The proposed approach is applied to IEEE 30 bus test system [62], [64]. Figure 5.1 shows the single line diagram of IEEE 30 bus system. Data of generators, loads, and transmission lines are given in tables 5.2-5.4. Consider the single scenario case which was described in section 5.3.1. PDFs of LMPs were computed for the peak load of planning horizon of existing network in section 5.3.1. If between each two buses that have average LMP difference greater than \$5/MWhr a new transmission line suggested as expansion candidate, we have 89 decision alternatives including alternative "do nothing". Stakeholders and their desires are weighted according to tables 7.2 and 7.3. Importance degrees of decision criteria (desires) from the viewpoint of transmission planners (U_i) are obtained by aggregating tables 7.2 and 7.3. Table 7.4 shows the importance degrees of decision criteria from the viewpoint of transmission planners. In this table the importance degree of each criterion is a triangular fuzzy number. Appropriateness degrees of expansion plans versus competition, reliability, flexibility of operation, network charge, and environmental impacts are computed using the criteria described in section 7.2. Average congestion cost is used to measure the competition. Columns 3-7 of table 7.5 show the appropriateness degrees of expansion plans versus different decision criteria. Fuzzy appropriateness index ($\mathcal{F}_{ap}^{k}$) was computed by aggregating importance degrees of decision criteria from the viewpoint of transmission planners (table 7.4) and appropriateness degrees of expansion plans versus decision criteria (columns 3-7 of table 7.5). Fuzzy appropriateness indices are shown in column 8 of table 7.5. Fuzzy appropriateness indices were ranked using different methods. Convex combination of right and left integral values with α=0.5 is shown in column 9 of table 7.5. All ranking method show that plan 3 i.e. line 1-10 has the greatest fuzzy appropriateness index and is selected as optimal plan. If the capacity of this line be greater than 325 MW, then the probability of violating its limit is less than one percent.

Table 7.4 - Importance degrees of decision criteria form viewpoint of transmission planners

Desire	Importance degree
Competition	(0.1125, 0.3125, 0.5375)
Reliability	(0.1250, 0.3875, 0.6625)
Flexibility of Operation	(0.0750, 0.2875, 0.6000)
Network Charge	(0.1125, 0.3250, 0.6250)
Environmental Impacts	(0.0375, 0.1250, 0.3250)

Table 7.5 – Appropriateness degrees of expansion plans versus decision criteria and fuzzy appropriateness indices

Plan No.	Expansion plan	Compet-ition	Reli-ability	Flex-ibility	Net.-Charge	Envir.-impacts	Fuzzy Appropriateness Index	Int. value α=0.5
1	Do nothing	0.4861	0.7176	0.4302	1.0000	1.0000	(0.0653, 0.2007, 0.3890)	0.2139
2	1 - 9	0.5228	0.8750	0.8243	0.1104	0.5141	(0.0523, 0.1679, 0.3183)	0.1766
3	1 - 10	1.0000	0.9856	0.8124	0.9540	0.1541	(0.0819, 0.2515, 0.4648)	0.2624
4	1 - 17	0.5983	0.5951	0.4360	0.4314	0.5186	(0.0485, 0.1496, 0.2831)	0.1577
5	1 - 19	0.5566	0.6350	0.4653	0.6220	0.7931	(0.0553, 0.1710, 0.3291)	0.1816
6	1 - 20	0.5569	0.7660	0.5051	0.1075	0.1491	(0.0428, 0.1339, 0.2451)	0.1389
7	1 - 21	0.6415	0.5313	0.5005	0.0980	0.5034	(0.0412, 0.1290, 0.2444)	0.1359
8	1 - 25	0.6096	0.5843	0.4281	0.8108	0.6895	(0.0582, 0.1779, 0.3405)	0.1886
9	1 - 26	0.6005	0.6108	0.4475	0.7958	0.9231	(0.0603, 0.1854, 0.3587)	0.1975
10	1 - 27	0.5907	0.6636	0.4376	0.8624	0.5832	(0.0602, 0.1841, 0.3496)	0.1945
11	1 - 28	0.5823	0.6261	0.5161	0.0617	0.9875	(0.0453, 0.1433, 0.2794)	0.1528
12	1 - 29	0.6130	0.6803	0.4486	0.4250	0.5070	(0.0509, 0.1571, 0.2959)	0.1653
13	1 - 30	0.5388	0.6207	0.3411	0.7525	0.7966	(0.0557, 0.1702, 0.3269)	0.1808
14	2 - 9	0.5192	0.9099	1.0000	0.9766	0.6413	(0.0762, 0.2400, 0.4601)	0.2541
15	2 - 10	0.9736	1.0000	0.7327	0.1052	0.1449	(0.0613, 0.1909, 0.3476)	0.1977
16	2 - 16	0.6218	0.6005	0.4950	0.3585	0.9927	(0.0519, 0.1620, 0.3152)	0.1728
17	2 - 17	0.5982	0.6220	0.4557	0.7412	0.7770	(0.0584, 0.1794, 0.3446)	0.1904
18	2 - 18	0.6086	0.5698	0.4175	0.3504	0.9354	(0.0491, 0.1524, 0.2956)	0.1624
19	2 - 19	0.5355	0.7056	0.5170	0.5668	0.1556	(0.0514, 0.1586, 0.2941)	0.1657
20	2 - 20	0.5345	0.8896	0.5866	0.6726	0.7070	(0.0635, 0.1975, 0.3757)	0.2085
21	2 - 21	0.6349	0.5772	0.5438	0.8195	0.3231	(0.0577, 0.1770, 0.3334)	0.1863
22	2 - 24	0.6208	0.5536	0.4563	0.7098	0.6045	(0.0552, 0.1692, 0.3229)	0.1791
23	2 - 25	0.6101	0.6336	0.4642	0.3287	0.2358	(0.0457, 0.1412, 0.2617)	0.1474
24	2 - 26	0.5907	0.6706	0.4913	0.6202	0.5819	(0.0557, 0.1720, 0.3267)	0.1816
25	2 - 27	0.5814	0.6941	0.4577	0.5670	0.8581	(0.0565, 0.1748, 0.3361)	0.1855
26	2 - 28	0.5204	0.5276	0.4349	0.8872	0.5169	(0.0553, 0.1690, 0.3225)	0.1790
27	2 - 29	0.5778	0.7886	0.5778	0.7389	0.0291	(0.0582, 0.1792, 0.3302)	0.1867
28	2 - 30	0.5186	0.7081	0.3891	0.5858	0.5137	(0.0522, 0.1606, 0.3029)	0.1691
29	3 - 29	0.5237	0.7141	0.4709	0.8787	0.4879	(0.0601, 0.1845, 0.3490)	0.1945
30	3 - 30	0.4955	0.6743	0.4042	0.5634	0.7426	(0.0523, 0.1617, 0.3098)	0.1714
31	4 - 29	0.5136	0.6935	0.4573	0.2938	0.4802	(0.0460, 0.1432, 0.2699)	0.1506
32	4 - 30	0.4998	0.6613	0.3634	0.0141	0.0606	(0.0340, 0.1058, 0.1907)	0.1091
33	5 - 19	0.4975	0.7288	0.4806	0.8023	0.4909	(0.0584, 0.1796, 0.3399)	0.1894
34	5 - 20	0.4808	0.7427	0.4081	0.3818	0.5231	(0.0480, 0.1490, 0.2808)	0.1567
35	5 - 21	0.4721	0.6659	0.3992	0.2869	0.8582	(0.0461, 0.1442, 0.2785)	0.1533
36	5 - 29	0.5325	0.7443	0.4908	0.9913	0.1672	(0.0615, 0.1878, 0.3495)	0.1967
37	5 - 30	0.4903	0.7215	0.4758	0.5278	0.5027	(0.0519, 0.1608, 0.3041)	0.1694
38	6 - 29	0.5000	0.6527	0.4304	0.3530	0.5805	(0.0463, 0.1440, 0.2737)	0.1520
39	6 - 30	0.4958	0.6454	0.3546	0.4511	0.4318	(0.0460, 0.1415, 0.2658)	0.1487
40	7 - 29	0.5294	0.6831	0.4504	0.9384	0.4173	(0.0600, 0.1834, 0.3459)	0.1932
41	7 - 30	0.4881	0.6785	0.4474	0.1903	0.3101	(0.0413, 0.1289, 0.2400)	0.1348
42	8 - 9	0.4966	0.9335	0.7694	0.3674	0.3707	(0.0571, 0.1808, 0.3394)	0.1895
43	8 - 10	0.6794	0.9009	0.7426	0.0793	0.5079	(0.0545, 0.1728, 0.3244)	0.1812
44	8 - 16	0.5638	0.7060	0.5172	0.0453	0.0576	(0.0395, 0.1241, 0.2256)	0.1283
45	8 - 17	0.5560	0.7291	0.5342	0.4854	0.9425	(0.0567, 0.1771, 0.3424)	0.1883
46	8 - 18	0.5481	0.6943	0.4578	0.8439	0.5271	(0.0595, 0.1824, 0.3456)	0.1925
47	8 - 19	0.5129	0.8989	0.6586	0.2665	0.8845	(0.0565, 0.1790, 0.3441)	0.1897
48	8 - 20	0.5078	0.9613	0.7043	0.2178	0.7336	(0.0564, 0.1792, 0.3414)	0.1891
49	8 - 21	0.5748	0.6951	0.6548	0.2540	0.0866	(0.0465, 0.1461, 0.2698)	0.1521
50	8 - 24	0.5473	0.6624	0.4854	0.1593	0.7107	(0.0451, 0.1416, 0.2710)	0.1498
51	8 - 25	0.5350	0.7702	0.4617	0.3308	0.5180	(0.0495, 0.1541, 0.2900)	0.1620
52	8 - 26	0.5172	0.7912	0.5217	0.8046	0.7230	(0.0628, 0.1940, 0.3706)	0.2054
53	8 - 27	0.5352	0.8253	0.5442	0.5694	0.8932	(0.0603, 0.1880, 0.3614)	0.1995
54	8 - 28	0.4823	0.8662	0.6347	0.6906	0.3964	(0.0605, 0.1886, 0.3549)	0.1981
55	8 - 29	0.5048	0.9126	0.5471	0.7437	0.8704	(0.0656, 0.2038, 0.3904)	0.2159
56	8 - 30	0.4828	0.7524	0.4135	0.2138	0.7570	(0.0464, 0.1451, 0.2771)	0.1534
57	9 - 29	0.4820	0.6950	0.5092	0.8160	0.9980	(0.0617, 0.1913, 0.3719)	0.2040
58	10 - 29	0.4735	0.7247	0.4779	0.3193	0.2818	(0.0452, 0.1410, 0.2625)	0.1474
59	11 - 9	0.5432	0.8464	0.6201	0.4671	0.6876	(0.0584, 0.1828, 0.3480)	0.1930
60	11 - 10	0.6841	0.7253	0.5979	0.3410	0.3734	(0.0530, 0.1648, 0.3083)	0.1727
61	11 - 16	0.5409	0.5180	0.3105	0.6965	0.1263	(0.0464, 0.1402, 0.2593)	0.1465
62	11 - 17	0.5242	0.5293	0.3173	0.9788	0.5776	(0.0561, 0.1701, 0.3245)	0.1802

63	11 - 18	0.5155	0.5203	0.2859	0.3246	0.4128	(0.0393, 0.1204, 0.2261)	0.1265
64	11 - 19	0.5074	0.6299	0.3776	0.1698	0.0589	(0.0371, 0.1148, 0.2084)	0.1187
65	11 - 20	0.5572	0.7440	0.5451	0.1856	0.7858	(0.0494, 0.1555, 0.2982)	0.1647
66	11 - 21	0.5133	0.5242	0.3457	0.8185	0.1320	(0.0492, 0.1491, 0.2770)	0.1561
67	11 - 24	0.5037	0.5077	0.2391	0.8101	0.0710	(0.0464, 0.1390, 0.2560)	0.1451
68	11 - 25	0.4827	0.5819	0.3488	0.0137	0.4616	(0.0344, 0.1078, 0.2026)	0.1131
69	11 - 26	0.4825	0.5672	0.3740	0.3259	0.4490	(0.0413, 0.1280, 0.2418)	0.1348
70	11 - 27	0.4994	0.6514	0.3905	0.1743	0.9223	(0.0442, 0.1385, 0.2686)	0.1475
71	11 - 28	0.5657	0.8002	0.5862	0.3723	0.6970	(0.0551, 0.1727, 0.3290)	0.1824
72	11 - 29	0.5048	0.7286	0.4805	0.0118	0.7868	(0.0429, 0.1361, 0.2611)	0.1441
73	11 - 30	0.4704	0.6515	0.3905	0.0675	0.2649	(0.0362, 0.1134, 0.2094)	0.1181
74	12 - 29	0.5265	0.7637	0.5596	0.2770	0.3102	(0.0479, 0.1500, 0.2797)	0.1569
75	13 - 29	0.5319	0.8059	0.5904	0.4099	0.8613	(0.0567, 0.1778, 0.3420)	0.1886
76	13 - 30	0.4776	0.7374	0.4052	0.7199	0.7795	(0.0573, 0.1766, 0.3383)	0.1872
77	14 - 29	0.5362	0.7961	0.6562	0.7568	0.1298	(0.0598, 0.1854, 0.3449)	0.1939
78	14 - 30	0.4728	0.7415	0.4445	0.1592	0.6268	(0.0441, 0.1386, 0.2631)	0.1461
79	15 - 29	0.5275	0.7768	0.6403	0.6508	0.4306	(0.0588, 0.1831, 0.3458)	0.1927
80	16 - 29	0.5044	0.7445	0.4909	0.4110	0.9180	(0.0535, 0.1671, 0.3228)	0.1776
81	17 - 29	0.4821	0.7323	0.4829	0.7211	0.9780	(0.0600, 0.1860, 0.3605)	0.1981
82	18 - 29	0.5258	0.8013	0.6605	0.7308	0.2893	(0.0604, 0.1877, 0.3521)	0.1970
83	22 - 29	0.5382	0.8135	0.5960	0.2306	0.7620	(0.0523, 0.1650, 0.3155)	0.1744
84	23 - 29	0.5349	0.8112	0.6686	0.1848	0.9877	(0.0539, 0.1714, 0.3325)	0.1823
85	24 - 29	0.4460	0.7808	0.4681	0.8728	0.0870	(0.0569, 0.1742, 0.3223)	0.1819
86	25 - 29	0.4456	0.7604	0.4179	0.9781	0.7917	(0.0633, 0.1942, 0.3725)	0.2060
87	26 - 29	0.4590	0.7635	0.4196	0.9356	0.3560	(0.0594, 0.1817, 0.3409)	0.1909
88	27 - 29	0.4740	0.7673	0.5059	0.0974	0.7086	(0.0449, 0.1422, 0.2716)	0.1502
89	28 - 29	0.4747	0.7283	0.4803	0.2438	0.1283	(0.0425, 0.1328, 0.2440)	0.1380

8 Stakeholders' Desires and Non-random Uncertainties

In chapter 7 a new transmission expansion planning approach was presented with consideration given to the stakeholders' desires using fuzzy decision making. The presented approach only takes into account random uncertainties and vagueness. In this chapter a transmission planning approach is presented with taking into account stakeholders' desires, random uncertainties, nonrandom uncertainties and vagueness [71]-[72]. This approach consists of combination of probabilistic locational marginal price, scenario technique, and fuzzy decision making. Fuzzy risk assessment is used for selecting the final plan.

This chapter is organized as follows. In section 8.1, the presented model for transmission expansion planning with considering stakeholders' desires, random uncertainties, non-random uncertainties and vagueness is overviewed. The model is described in detail in section 8.2. The approach is applied to an eight bus test systems in section 8.3.

8.1 Model Overview

Consider a network and assume we want to design a transmission expansion plan for a specified planning horizon. Suppose PDFs of random inputs were determined for the peak load of planning horizon. The approach consists of the following steps:

1) Identifying the set of possible strategic scenarios (refer to 5.2.1)
2) Suggesting candidates for transmission expansion by analyzing the electric market (refer to 5.2.2)
3) Computing fuzzy appropriateness index for each plan in each scenario (refer to 7.4.1)
4) Computing fuzzy regret and selecting the final plan using fuzzy risk assessment (refer to 8.2.1)
5) Computing the capacity of selected expansion plan (refer to 5.2.5)

8.2 Model in detail

Steps 1 and 2 are the same as chapters 5 and 6. In step 3 the fuzzy appropriateness index, which is defined in chapter 7 for measuring the goodness of expansion plans, is computed for each plan in each scenario. The fuzzy appropriateness index is computed by aggregating importance weights of stakeholders in decision making, importance degrees of stakeholders' desires from the viewpoint of different stakeholders, and appropriateness degrees of expansion plans versus stakeholders' desires using equations (7.1)-(7.7). Step 4 is described in detail in the following subsections. Step 5 is the same as chapters 5 and 6.

8.2.1 Fuzzy Regret and Risk Assessment

Suppose $\mathcal{F}_{ap}^{k,l}$ is the fuzzy appropriateness index of plan *k* in scenario *l* which was computed in step 3. After computing the fuzzy appropriateness index for each plan in each scenario, we have a table of fuzzy appropriateness indices, i.e. $\mathcal{F}_{ap}^{k,l}$ for $k = 1,\ldots, N_p$, and $l = 1,\ldots, N_s$. The final plan must be selected by taking into account the occurrence degrees of future scenarios. Due to vagueness in occurrence degrees of future scenarios, the following linguistic variables are used to represent the occurrence degrees of scenarios:

$$Z = \{\text{VL, L, M, H, VH}\}$$

where VL, L, M, H, and VH are abbreviations of very low, low, medium, high, and very high respectively. A triangular fuzzy number is assigned to each linguistic variable according to table 6.6.

Definition:

Weighted fuzzy regret of plan *k* in scenario *l* is equal to difference between the fuzzy appropriateness index of plan *k* in scenario *l* and fuzzy appropriateness index of optimal plan of scenario *l* multiplied by the occurrence degree of scenario *l*:

$$\mathcal{R}^{k,l} = Z^l \otimes (\mathcal{F}_{ap}^{op,l} \ominus \mathcal{F}_{ap}^{k,l}) \tag{8.1}$$

with:

$\mathcal{R}^{k,l}$	fuzzy regret of plan *k* in scenario *l*
$Z^l \in Z$	occurrence degree of scenario *l*
$\mathcal{F}_{ap}^{k,l}$	fuzzy appropriateness index of plan *k* in scenario *l*
$\mathcal{F}_{ap}^{op,l}$	fuzzy appropriateness index of the optimal plan of scenario *l*

$\ominus$ fuzzy subtraction operator

Optimal plan of scenario l is the plan which has the maximum fuzzy appropriateness index in scenario l. Fuzzy subtraction is defined using α-cuts of fuzzy intervals [74]-[75].

Now we have a table of fuzzy regrets and the final plan must be selected. Fuzzy risk assessment with the criteria maximum regret, average regret, degree of robustness of order 1, …, and degree of robustness of order 5 is used for selecting the final plan (see chapter 6). The difference between risk assessment in this chapter and chapter 6 is that regrets in this chapter are fuzzy numbers while in chapter 6 regrets were real numbers. For risk assessment the appropriateness degrees of expansion plans versus decision criteria must be determined. To compute appropriateness degrees of expansion plans versus maximum regret, and degree of robustness of order *m*, first a crisp value is assigned to each fuzzy regret. This crisp value can be x of centroid point, distance of centroid point from zero, distance of extended centroid point from zero, or convex combination of right and left integral values of fuzzy regrets [27], [75]-[77]. Then, the method which was described in chapter 6 is used for determining the appropriateness degrees of expansion plans versus maximum regret, and degree of robustness of order *m* (see equations (6.1)-(6.3)).To compute the appropriateness degrees of expansion plans versus average regret, first the average of fuzzy regrets of each plan over different scenarios is computed using fuzzy mean operator. Then, a crisp number is assigned to each average regret. After that, inverse of the crisp values are computed and normalized on their maximum value over different plans. After determining the appropriateness degrees of expansion plans versus different decision criteria, fuzzy appropriateness index (F_{ap}^{k}) is computed for selecting the final plan from the table of fuzzy regrets. This fuzzy appropriateness index is computed by aggregating the appropriateness degrees of expansion plans versus decision criteria and importance degree of decision criteria using equation (6.4). The plan which has the greatest fuzzy appropriateness index is selected as the final plan. See chapter 6 for more detail in fuzzy risk assessment.

8.3 Case Study

The presented approach is applied to the eight bus test system which is shown in Fig. 8.1 [62]-[64]. Data of generators, loads, and tie-lines for the peak load of planning horizon are given in tables 3.1 to 3.3. Parameters of transmission lines are given in table 3.4. Mean of generation power, mean of load, mean of power of lines, and mean of LMPs for the peak load of planning horizon are shown in figure 8.1. The generator of bus 4 may be closed. If the

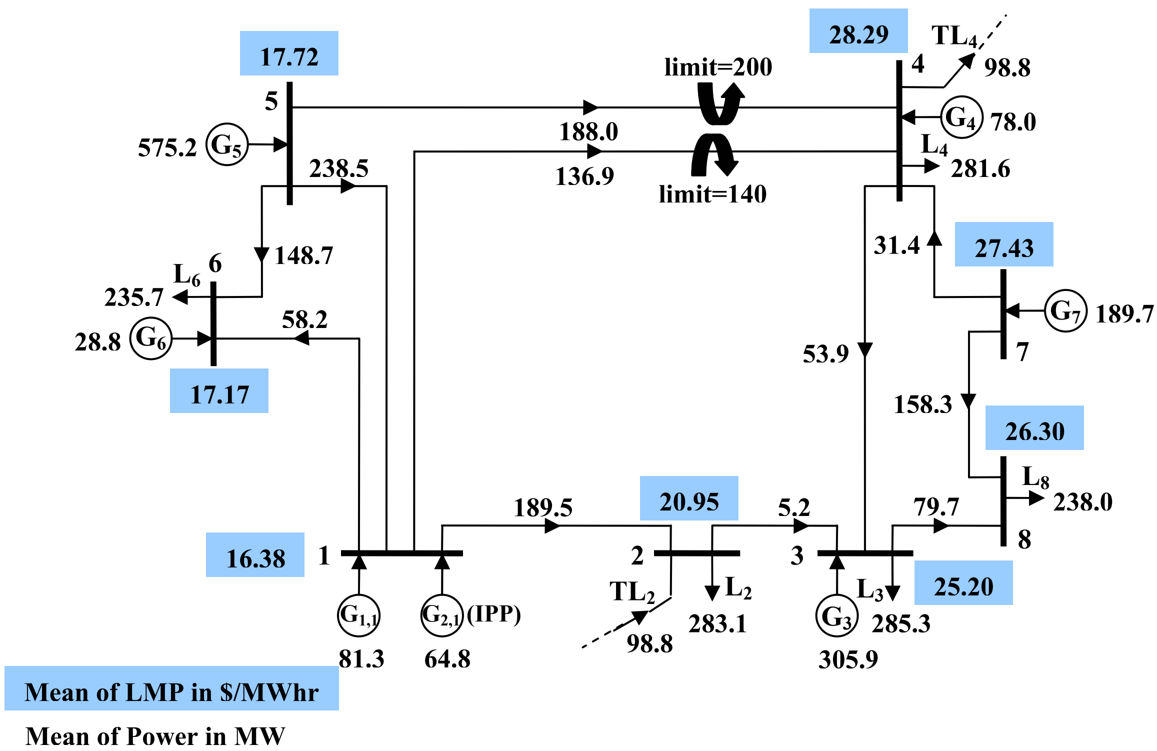


Fig. 8.1- Single line diagram of the eight bus test system

Table 8.1 - Characteristics of new generator and IPP

Bus No.	Type	Min (MW)	Max (MW)	PDFof Bid ($/MWhr)	Unavailability
4	Gen.	0	150	N~(22, 3)	0.02
4	IPP	0	N~(100, 20)	N~(20, 2)	0.02

generator of bus 4 is closed, either a new generator or a new IPP may be installed in this bus. Characteristics of the new generator and IPP are given in table 8.1. The steps of transmission expansion planning are described in bellow.

1) Identifying the set of possible strategic scenarios

The following scenarios are defined to cover above non-random uncertainties:

Scenario 1: Base case

Scenario 2: Base case minus the generator of bus 4

Scenario 3: Base case minus the generator of bus 4 plus the new generator

Scenario 4: Base case minus the generator of bus 4 plus the new IPP

Occurrence degrees of above scenarios are low, high, medium, and high respectively.

2) Suggesting candidates for transmission expansion

PDFs of LMPs are computed for the peak load of planning horizon of the existing network at different scenarios. If between each two buses that have average LMP difference greater than

\$8/MWhr a new transmission line is suggested as expansion candidate, 12 candidates will result. The set of transmission candidates is as bellow:

{do nothing, line 1-3, line 1-4, line 1-7, line 1-8, line 5-3, line 5-4, line 5-7, line 5-8, line 6-3, line 6-4, line 6-7, line 6-8 }

3) Computing fuzzy appropriateness index

Importance degrees of stakeholders' desires from the viewpoint of transmission planners (U_i) were computed by aggregating importance degrees of stakeholders in decision making (tables 7.2) and importance degrees of stakeholders' desires from viewpoint of different stakeholders (table 7.3) using equation (7.3). Importance degrees of stakeholders' desires from the viewpoint of transmission planners are given in table 7.4. Appropriateness degrees of expansion plans versus stakeholders' desire are computed for each scenario using the criteria presented in section 7.2 and equations (7.1)-(7.2). Table 8.2 shows the appropriateness degrees of expansion plans versus stakeholders' desires in different scenarios. Network charge and environmental impacts of expansion plans are the same in scenarios 1 to 4. Fuzzy appropriateness index ($\mathcal{F}_{ap}^{k}$) for measuring the goodness of expansion plans versus combination of all decision criteria is computed for each plan in each scenario by aggregating importance degrees of stakeholders' desires (tables 7.4) and appropriateness degrees of expansion plans (table 8.2) using equation (7.7). Table 8.3 shows the fuzzy appropriateness index of expansion plans in different scenarios. In this table the optimal plan of each scenario was marked. All the ranking methods select the same optimal plan.

4) Computing the fuzzy regret and selecting the final plan using fuzzy risk assessment

Fuzzy regret of each plan in each scenario is computed by considering occurrence degrees of future scenarios using equation (8.1). Table 8.4 shows the fuzzy regret of expansion plans in different scenarios. Fuzzy risk assessment is applied to table 8.4 for selecting the final plan. Maximum regret, average regret, and degree of robustness of order one to five are computed for each plan. Maximum regret, average regret, and degree of robustness of order one to five will be as columns 2-8 of table 8.5, if convex combination of right and left integral values with α=0.5 is used for assigning a crisp value to fuzzy regrets. Fuzzy appropriateness index (F_{ap}^{k}) is computed for selecting the final plan by aggregating importance degrees of decision criteria (table 6.5) and appropriateness degrees of expansion plans versus decision criteria (columns 2-8 of table 8.5). Column 9 of table 8.5 shows the appropriateness indices. Convex combination of right and left integral values of fuzzy appropriateness indices with α=0.5 are shown in column 10 of table 8.5. Line 5-4 has the maximum fuzzy appropriateness index and is selected as the final plan.

If right integral value, convex combination of right and left integral values with α=0.5, x of centroid point, or distance of centroid point from zero is used for ranking fuzzy appropriateness indices, line 5-4 is selected as the final plan. If left integral value is used for ranking fuzzy appropriateness indices, plan do nothing is selected as the final plan. If distance of extended centroid point from zero is used for ranking fuzzy appropriateness indices, line 5-8 selected as the final plan.

5) Computing the capacity of selected expansion plan

Capacity of line 5-4 and line 5-8 must be greater than 359 MW and 424 MW respectively, in order to ensure the probability of violating their limits is less than one percent in all scenarios during the peak load of planning horizon.

Table 8.2- Appropriateness degrees of expansion plans versus stakeholders' desires in different scenarios

	Competition				Reliability				Flexibility of Operation				Net. Cha.	Env. Imp.
	S1	S2	S3	S4	S1	S2	S3	S4	S1	S2	S3	S4	S1-S4	S1-S4
Do nothing	0.28	0.25	0.30	0.27	0.51	0.13	0.38	0.27	0.30	0.07	0.22	0.16	1.0	1.0
Line 1-3	0.38	0.33	0.62	0.37	0.65	0.11	0.61	0.33	0.25	0.06	0.23	0.13	0.60	0.70
Line 1-4	0.42	0.41	0.54	0.48	0.62	0.39	0.70	0.61	0.24	0.15	0.20	0.18	0.75	0.50
Line 1-7	0.41	0.39	0.42	0.40	0.67	0.23	0.64	0.45	0.39	0.13	0.25	0.26	0.80	0.55
Line 1-8	0.42	0.38	0.70	0.42	0.79	0.24	1.0	0.61	0.31	0.14	0.39	0.24	0.72	0.65
Line 5-4	0.56	0.54	0.63	0.62	0.56	0.47	0.69	0.57	0.22	0.18	0.41	0.33	0.79	0.72
Line 5-7	0.46	0.42	0.62	0.46	0.66	0.21	0.68	0.48	0.39	0.12	0.27	0.19	0.69	0.68
Line 5-8	0.47	0.41	1.0	0.58	0.78	0.15	0.85	0.56	0.45	0.09	1.0	0.33	0.70	0.57
Line 5-3	0.42	0.35	0.80	0.43	0.59	0.08	0.56	0.28	0.35	0.04	0.66	0.33	0.65	0.70
Line 6-3	0.32	0.26	0.49	0.31	0.45	0.04	0.33	0.14	0.26	0.02	0.19	0.08	0.75	0.50
Line 6-4	0.30	0.27	0.45	0.41	0.60	0.35	0.61	0.52	0.23	0.20	0.23	0.20	0.77	0.55
Line 6-7	0.30	0.26	0.33	0.30	0.50	0.11	0.42	0.26	0.29	0.06	0.16	0.15	0.68	0.63
Line 6-8	0.36	0.30	0.65	0.37	0.57	0.08	0.52	0.29	0.33	0.05	0.20	0.17	0.72	0.68

Table 8.3- Fuzzy appropriateness index ($\mathcal{F}_{ap}^{k}$) of expansion plans in different scenarios, optimal plans are marked

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Do noth.	(0.0448, 0.1487, 0.3030)	(0.0323, 0.1072, 0.2272)	(0.0414, 0.1368, 0.2809)	(0.0375, 0.1240, 0.2577)
Line 1-3	(0.0415, 0.1343, 0.2625)	(0.0254, 0.0817, 0.1683)	(0.0456, 0.1452, 0.2805)	(0.0322, 0.1037, 0.2073)
Line 1-4	(0.0423, 0.1378, 0.2671)	(0.0357, 0.1160, 0.2277)	(0.0461, 0.1487, 0.2848)	(0.0425, 0.1373, 0.2648)
Line 1-7	(0.0464, 0.1526, 0.2978)	(0.0322, 0.1052, 0.2108)	(0.0441, 0.1440, 0.2801)	(0.0393, 0.1289, 0.2543)
Line 1-8	(0.0479, 0.1559, 0.3021)	(0.0320, 0.1038, 0.2092)	(0.0600, 0.1927, 0.3664)	(0.0427, 0.1385, 0.2709)
Line 5-4	(0.0458, 0.1476, 0.2886)	(0.0430, 0.1385, 0.2723)	(0.0535, 0.1728, 0.3358)	(0.0493, 0.1590, 0.3105)
Line 5-7	(0.0468, 0.1521, 0.2972)	(0.0319, 0.1028, 0.2069)	(0.0490, 0.1571, 0.3029)	(0.0399, 0.1285, 0.2525)
Line 5-8	(0.0501, 0.1634, 0.3161)	(0.0291, 0.0940, 0.1893)	(0.0715, 0.2307, 0.4416)	(0.0457, 0.1475, 0.2859)
Line 5-3	(0.0434, 0.1410, 0.2771)	(0.0256, 0.0823, 0.1699)	(0.0558, 0.1793, 0.3484)	(0.0362, 0.1178, 0.2366)
Line 6-3	(0.0365, 0.1203, 0.2376)	(0.0223, 0.0736, 0.1524)	(0.0366, 0.1185, 0.2326)	(0.0268, 0.0879, 0.1782)
Line 6-4	(0.0396, 0.1306, 0.2563)	(0.0330, 0.1091, 0.2187)	(0.0433, 0.1407, 0.2734)	(0.0398, 0.1297, 0.2539)
Line 6-7	(0.0375, 0.1232, 0.2447)	(0.0245, 0.0801, 0.1657)	(0.0345, 0.1124, 0.2232)	(0.0299, 0.0980, 0.1983)
Line 6-8	(0.0421, 0.1380, 0.2727)	(0.0254, 0.0828, 0.1720)	(0.0457, 0.1458, 0.2826)	(0.0335, 0.1091, 0.2194)

Table 8.4 - Fuzzy regrets of expansion plans in different scenarios

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Do noth.	(0.0322, 0.2020, 0.4971)	(0.0549, 0.2188, 0.4850)	(0.0450, 0.2459, 0.6008)	(0.0469, 0.2187, 0.5080)
Line 1-3	(0.0434, 0.2096, 0.4997)	(0.0722, 0.2327, 0.4905)	(0.0451, 0.2414, 0.5975)	(0.0615, 0.2297, 0.5122)
Line 1-4	(0.0421, 0.2077, 0.4990)	(0.0547, 0.2140, 0.4824)	(0.0439, 0.2396, 0.5971)	(0.0448, 0.2115, 0.5041)
Line 1-7	(0.0337, 0.2000, 0.4958)	(0.0597, 0.2199, 0.4851)	(0.0452, 0.2421, 0.5987)	(0.0479, 0.2161, 0.5065)
Line 1-8	(0.0325, 0.1983, 0.4947)	(0.0602, 0.2206, 0.4853)	(0.0210, 0.2163, 0.5863)	(0.0431, 0.2109, 0.5039)
Line 5-4	(0.0362, 0.2026, 0.4963)	(0.0415, 0.2017, 0.4765)	(0.0296, 0.2268, 0.5913)	(0.0316, 0.1998, 0.4987)
Line 5-7	(0.0338, 0.2002, 0.4956)	(0.0608, 0.2212, 0.4854)	(0.0388, 0.2352, 0.5948)	(0.0484, 0.2163, 0.5061)
Line 5-8	(0.0286, 0.1943, 0.4930)	(0.0660, 0.2260, 0.4876)	(0, 0.1961, 0.5773)	(0.0387, 0.2060, 0.5015)
Line 5-3	(0.0394, 0.2060, 0.4982)	(0.0718, 0.2323, 0.4904)	(0.0261, 0.2234, 0.5896)	(0.0530, 0.2221, 0.5090)
Line 6-3	(0.0502, 0.2169, 0.5035)	(0.0769, 0.2371, 0.4930)	(0.0585, 0.2556, 0.6045)	(0.0699, 0.2382, 0.5164)
Line 6-4	(0.0451, 0.2115, 0.5011)	(0.0574, 0.2178, 0.4845)	(0.0471, 0.2438, 0.5993)	(0.0480, 0.2156, 0.5062)
Line 6-7	(0.0483, 0.2154, 0.5027)	(0.0730, 0.2336, 0.4913)	(0.0611, 0.2588, 0.6062)	(0.0641, 0.2328, 0.5140)
Line 6-8	(0.0405, 0.2076, 0.4991)	(0.0711, 0.2320, 0.4905)	(0.0445, 0.2412, 0.5974)	(0.0580, 0.2268, 0.5111)

Table 8.5 – Values of decision criteria, Fuzzy appropriateness index (F_{ap}^{k}), and convex combination of right and left integral values

	MR	AR	DR1	DR2	DR3	DR4	DR5	Fuzzy appropriateness index	IV-0.5
Do noth.	0.8839	0.9497	0	0.5	0	0	0.5	(0.1667, 0.2500, 0.3512)	0.2545
Line 1-3	0.8935	0.9250	0	0	0	0.5	0	(0.1299, 0.2127, 0.2955)	0.2127
Line 1-4	0.8977	0.9561	0	0	0	1	0.5	(0.1324, 0.2343, 0.3541)	0.2388
Line 1-7	0.8914	0.9526	0	0.5	0	0	0	(0.1674, 0.2511, 0.3349)	0.2511
Line 1-8	0.9670	0.9792	1	0	0	0	0.5	(0.2462, 0.3514, 0.4387)	0.3469
Line 5-4	0.9358	0.9933	1	1	0	0	0	(0.3164, 0.4567, 0.5613)	0.4478
Line 5-7	0.9108	0.9571	0	0.5	0	0	0	(0.1691, 0.2537, 0.3383)	0.2537
Line 5-8	1.0	1.0	1	0	0	0.5	0.5	(0.2500, 0.3750, 0.4821)	0.3705
Line 5-3	0.9465	0.9488	0	0	1	0	0	(0.1711, 0.2745, 0.3779)	0.2745
Line 6-3	0.8563	0.8990	0	0	0	0	0	(0.1254, 0.1881, 0.2508)	0.1881
Line 6-4	0.8867	0.9438	0	0	0	0	1	(0.1307, 0.1961, 0.2972)	0.2050
Line 6-7	0.8486	0.9047	0	0	0	0	0	(0.1252, 0.1879, 0.2505)	0.1879
Line 6-8	0.8944	0.9297	0	0	0	0.5	0	(0.1303, 0.2133, 0.2963)	0.2133

* MR=Max regret, AV=Average regret, DR*i*=Degree of robustness of order *i*, IV-0.5= convex combination of right and left integral value with α=0.5

9 Conclusions

The main goal of this thesis was to present a centralized static approach for transmission expansion planning in deregulated power systems. Restructuring and deregulation have unbundled the roles of network stakeholders and exposed transmission planner to the new objectives and uncertainties. Unbundling the roles has brought new challenges for stakeholders. In these environments, stakeholders have different desires and expectations from the performance and expansion of the system. Therefore, new incentives and disincentives have emerged regarding transmission expansion decisions. This research work was involving with considering new objectives and uncertainties in transmission expansion planning.

This research work was handled in six main parts. In the first part a probabilistic tool was presented for analyzing the performance of electric markets (chapter 3). In the second part market based criteria were presented to measure how much an expansion plan facilitates and promotes competition (chapter 4). In the third part a market based transmission expansion planning was presented using the probabilistic tool which presented in the first part and the market based criteria which were presented in the second part (chapter 5). In the fourth part fuzzy decision making was used for the risk assessment of solutions (chapter 6). In the fifth part an approach was presented to take into account stakeholders' desires in transmission expansion planning (chapter 7). In the sixth part the presented approach was extended to consider stakeholders' desires under non-random uncertainties (chapter 8).

In the first part of the work, the concept of locational marginal pricing was described. Biding procedure in deregulated power systems was explained. A mathematical model for computing the locational marginal prices was introduced. The reason of using the probability density functions of locational marginal prices for analyzing electric markets was described. An algorithm for computing the probability density functions of locational marginal prices using Monte Carlo simulation was presented. The approach was applied to an 8-bus network, and the effects of load curtailment and wheeling power on nodal prices were studied. The study shows that wheeling transactions affect the locational marginal prices of the control area which transmit through them. It also shows that making wheeling transaction in proper directions can reduce the transmission congestion and postpone transmission expansion.

In the second part, requirements of competitive markets were discussed. In competitive markets there is no price discrimination among producers and consumers. In this market customers do not have any restriction to buy from any producer. To have a competitive electric market, the above conditions must be satisfied. On the other word, locational marginal prices must be made equal at all buses and transmission congestion must be alleviated. Based on theses conditions, two market based criteria were presented to measure how much an expansion plan facilitates competition. The criteria are “average congestion cost” and “weighted standard deviation of mean of locational marginal prices”. Different weights were used in order to provide a competitive environment for more power system participants. Justification of costs is very important in competitive environments. Therefore the presented criteria were extended in order to consider transmission expansion costs.

In the third part of the work, a transmission expansion planning approach was presented for deregulated environments. This approach consists of scenario technique and probabilistic optimal power flow which was presented in the first part. Scenario technique was used to take into account the non-random uncertainties. Probabilistic optimal power flow was used to consider the random uncertainties. The approach uses the market based criteria to measure the goodness of expansion plans. Market based criteria provide a non-discriminatory competitive environment for stakeholders. Minimax regret criterion was used in scenario technique for risk assessment and selecting the final plan. To determine which criterion leads to zero congestion cost and flat price profile at minimum cost or at minimum number of expansion plans, the presented approach was applied on IEEE 30 bus test system. Two different cases were considered. In case A, it was assumed that there is not any non-random uncertainty. The result of simulation shows that “average congestion cost” is a more efficient criterion than others if there is not any non-random uncertainty. In case B, it was assumed that there is non-random uncertainty. Eight different scenarios were defined to cover all non-random uncertainties. The result of simulation shows that “weighted standard deviation of mean of locational marginal prices” with the weight “sum of mean of generation and load” is as efficient as “average congestion cost” in multi scenario cases. The sensitivity analysis shows that “average congestion cost” is less insensitive than other criteria to the occurrence degrees of future scenarios.

Conventional risk assessment has some drawbacks. In the fourth part, drawbacks of scenario technique criteria were pointed out. New criteria were presented for the scenario technique including degree of robustness of order 1-5. Fuzzy multi criteria decision making was used for the risk assessment of solutions. In this method a fuzzy appropriateness index is defined for selecting the final plan. The fuzzy appropriateness index is computed by aggregation of importance degrees of decision criteria and appropriateness degrees of expansion plans versus decision criteria. The presented approach is applied to IEEE 30 bus test system and the result was compared with conventional risk assessment in different cases. The comparison shows that fuzzy risk assessment overcomes the shortcomings of conventional risk assessment method.

In the fifth part of the work, a transmission expansion planning approach with consideration given to stakeholders' desires was presented. The approach considers the desires of demand customers, power producers, network owner(s), system operator, and regulator in transmission expansion planning. Stakeholders' desires can be sought in competition, reliability, flexibility, network charge and environmental impacts. Fuzzy decision making was used for taking into account the desires of all stakeholders. A fuzzy appropriateness index is defined for measuring the goodness of expansion plans. The fuzzy appropriateness index is defined by aggregating importance weights of stakeholders in decision making, importance degrees of stakeholders' desires from the viewpoint of different stakeholders, and appropriateness degrees of expansion plans versus stakeholders' desires. The approach was applied to IEEE 30 bus test systems to find the plan which compromise between stakeholders' desires.

The presented approach in the fifth part can not consider non-random uncertainties. In the sixth part, the presented approach was extended to consider stakeholders' desires under non-random uncertainties. The fuzzy appropriateness index, which is defined in part five for measuring the goodness of expansion plans, is computed for each expansion plan in each scenario. Fuzzy regret was defined with considering the occurrence degrees of future scenarios. Fuzzy risk assessment was used to find the final plan. The steps of planning were described in details by applying the approach to an eight bus system.

Appendices

Appendix A: Examples on Scenario Technique Criteria

Consider a network and suppose three future scenarios are identified for this network. Network engineers suggest three expansion plans for transmission expansion planning of this network. Occurrence degrees of scenarios and costs of expansion plans in different scenarios are given in table A.1. In this example the final plan is selected using different scenario technique criteria [14], [19].

Table A.1- Cost of suggested expansion plans in identified scenarios

	Scenario A	Scenario B	Scenario C
Plan 1	100	116	144
Plan 2	120	118	124
Plan 3	128	104	120
Occurrence degree	0.25	0.5	0.25

A) Expected cost criterion

Expected cost of each plan over different scenarios is given in table A.2. Plan 3 has the minimum expected cost and is selected as the final plan.

Table A.2- expected cost of expansion plans in different scenarios

	Scenario A	Scenario B	Scenario C	Expected cost
Plan 1	100	116	144	119
Plan 2	120	118	124	120
Plan 3	128	104	120	114 ✓
Occurrence degree	0.25	0.5	0.25	

B) Minimax regret criterion

The optimal plan of each scenario is specified with an arrow in table A.3. Table A.4 shows the regrets of expansion plans in different scenarios. The weighted regrets of expansion plans are shown in table A.5. Maximum weighted regret of each plan is specified with an arrow in this table. Plan 1 has the minimum maximum weighted regret and is selected as the final plan.

Table A.3- Optimal plan of each scenario

	Scenario A	Scenario B	Scenario C
Plan 1	100	116	144
Plan 2	120	118	124
Plan 3	128	104	120
Occurrence degree	0.25	0.5	0.25

Table A.4- Regrets of expansion plans in different scenarios

	Scenario A	Scenario B	Scenario C
Plan 1	0	12	24
Plan 2	20	14	4
Plan 3	28	0	0
Occurrence degree	0.25	0.5	0.25

Table A.5- Weighted regrets of expansion plans in different scenarios

	Scenario A	Scenario B	Scenario C	Max weighted regret
Plan 1	0	6	6	6 ✓
Plan 2	5	7	1	7
Plan 3	7	0	0	7

C) Von Neumann-Morgestern criterion

C.1) Extremely pessimistic criterion

The most unfavourable scenario for each plan is specified with an arrow in table A.6. Plan 2 has the minimum maximum cost and is selected as the final plan.

Table A.6- Extremely pessimistic criterion

	Scenario A	Scenario B	Scenario C	Maximum cost
Plan 1	100	116	144	144
Plan 2	120	118	124	124 ✓
Plan 3	128	104	120	128

C.2) Extremely optimistic criterion

The most favourable scenario for each plan is specified with an arrow table A.7. Plan 1 has the minimum minimum cost and is selected as the final plan.

Table A.7- Extremely optimistic criterion

	Scenario A	Scenario B	Scenario C	Minimum cost
Plan 1	100	116	144	100 ✓
Plan 2	120	118	124	118
Plan 3	128	104	120	104

D) Hurwicz criterion

Maximum and minimum cost of each plan is shown in tables A.6 and A. 7. Convex combinations of maximum and minimum costs for plan 1 to 3 are as bellow:

Plan 1: $144\alpha+100\ (1-\alpha)$

Plan 2: $124\alpha+118\ (1-\alpha)$

Plan 3: $128\alpha+104\ (1-\alpha)$

Convex combination of maximum and minimum cost of each plan is drawn in figure A.1. This figure shows that plan 3 has the minimum convex combination in a wide range i.e. for $\alpha \in [0.2 \;\; 0.77]$. Hence plan 3 is selected as the final plan.

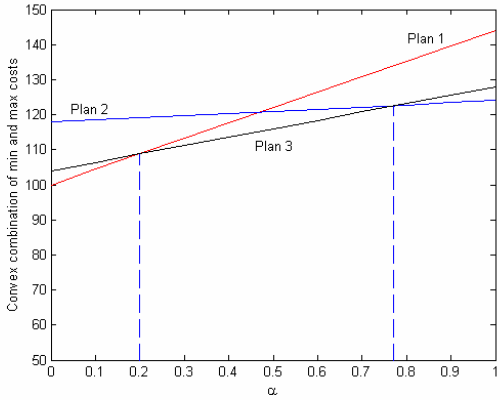


Fig A.1- Convex combination of max and min costs

E) Robustness criterion

Regrets of different expansion plans are shown in table A.8. Arrows show the zero regrets. Degree of robustness of each plan is shown in this table. Plan 3 has the maximum degree of robustness and is selected as the final plan.

Table A.8- Regrets of expansion plans in different scenarios

	Scenario A	Scenario B	Scenario C	Degree of robustness
Plan 1	0	12	24	%33.33
Plan 2	20	14	4	0
Plan 3	28	0	0	%66.66

F) β-robustness criterion

Optimal plan of each scenario is specified in table A.9. The overcost of each plan with respect to the related optimal plan is shown in table A.10. Maximum overcost of each plan is specified with an arrow in this table. Plans 1 and 2 have the minimum maximum overcost. Each of them can be selected as the final plan according to this criterion.

Table A.9- Cost of expansion plans in different scenarios

	Scenario A	Scenario B	Scenario C
Plan 1	100	116	144
Plan 2	120	118	124
Plan 3	128	104	120

Table A.10- Overcost of expansion plans in different scenarios

	Scenario A	Scenario B	Scenario C	Max overcost
Plan 1	0	%11.54	%20	%20
Plan 2	%20	%13.46	%3.33	%20
Plan 3	%28	0	0	%28

G) Pareto-Optimal criterion

Consider another example with 6 expansion plans and two scenarios. Cost of expansion plans are given in table A.11. Costs of expansion plans in scenarios A and B are drawn in figure A.2. As table A.11 and figure A.2 show, costs of plan 5 are greater than costs of plans 2 and 3 in both scenarios A and B. Thus, plan 5 is dominated by plans 2 and 3. Costs of plan 6 are greater than costs of plan 3 in scenarios A and B. Thus, plan 6 is dominated by plan 3. Plans 1, 2, 3 and 4 are not dominated by any other plan. Hence, Plans 1, 2, 3 and 4 are Pareto-optimal options.

Table A.11- Cost of expansion plans in scenarios A and B

	Scenario A	Scenario B
Plan 1	40	150
Plan 2	60	100
Plan 3	100	50
Plan 4	150	30
Plan 5	110	140
Plan 6	130	70

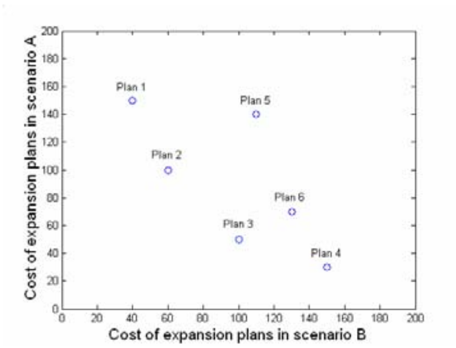


Fig A.2- Cost of expansion plans in scenarios A and B

Appendix B: An Example on Decision Analysis

Consider an industrial area which is supplied by a medium voltage under ground system [14]. Decision must be taken about reinforcement of the power network to meet the following loads:

- Load increase by existing consumers
- Uncertain load A which may be connected to the network at the beginning of year 5
- Uncertain load B which may be connected to the network at the beginning of year 7

Occurrence degree (probability of occurrence) of establishing loads A and B is equal to 0.7 and 0.6 respectively. As a first decision, the planners must select one of the following options:

- Reinforce the network by a double-circuit line on the subtransmission level with only one circuit (DCL-FC). The second circuit may be installed later (DCL-SC) in the planning period.
- Reinforce the network by a single-circuit line on the subtransmission level (SCL).
- Reinforce the network by a medium voltage cable (MVC).

Decision must be made at the beginning of year one, five or seven. Above decisions may be repeated later on the second or third investment decisions. Due to the growth of the existing load, the first decision can not consist of a “do nothing” decision. The costs of expansion plans, which are discounted to the beginning of year 1 with the interest rate 6 percent, are given in table B.1. The entire decision process is described in figure B.1. In this figure each circle represents a decision node and each square represents an events node. The following expansion plans can meet both load A and B:

- double-circuit line with two circuits, and
- two single-circuit lines.

The following expansion plans can meet either load A or B:

- medium voltage cable plus double-circuit line with one circuits, and
- medium voltage cable plus single-circuit line.

Table B.1- Discounted costs of expansion plans

	Beginning of year 1	Beginning of year 5	Beginning of year 7
Double-circuit line, first circuit	30	23.76	21.15
Double-circuit line, second circuit	6	4.75	4.23
Single-circuit line	20	15.84	14.10
Medium voltage cable	14	11.09	9.87

As figure B.1 shows, at the first stage of decision we can make on of the following decisions:

- double-circuit line with the first circuit,
- single-circuit line, or
- medium voltage cable.

Consider figure B.1 and suppose the network is reinforced by double-circuit line with the first circuit. If load A is added at the beginning of year 5, we can make one of the following

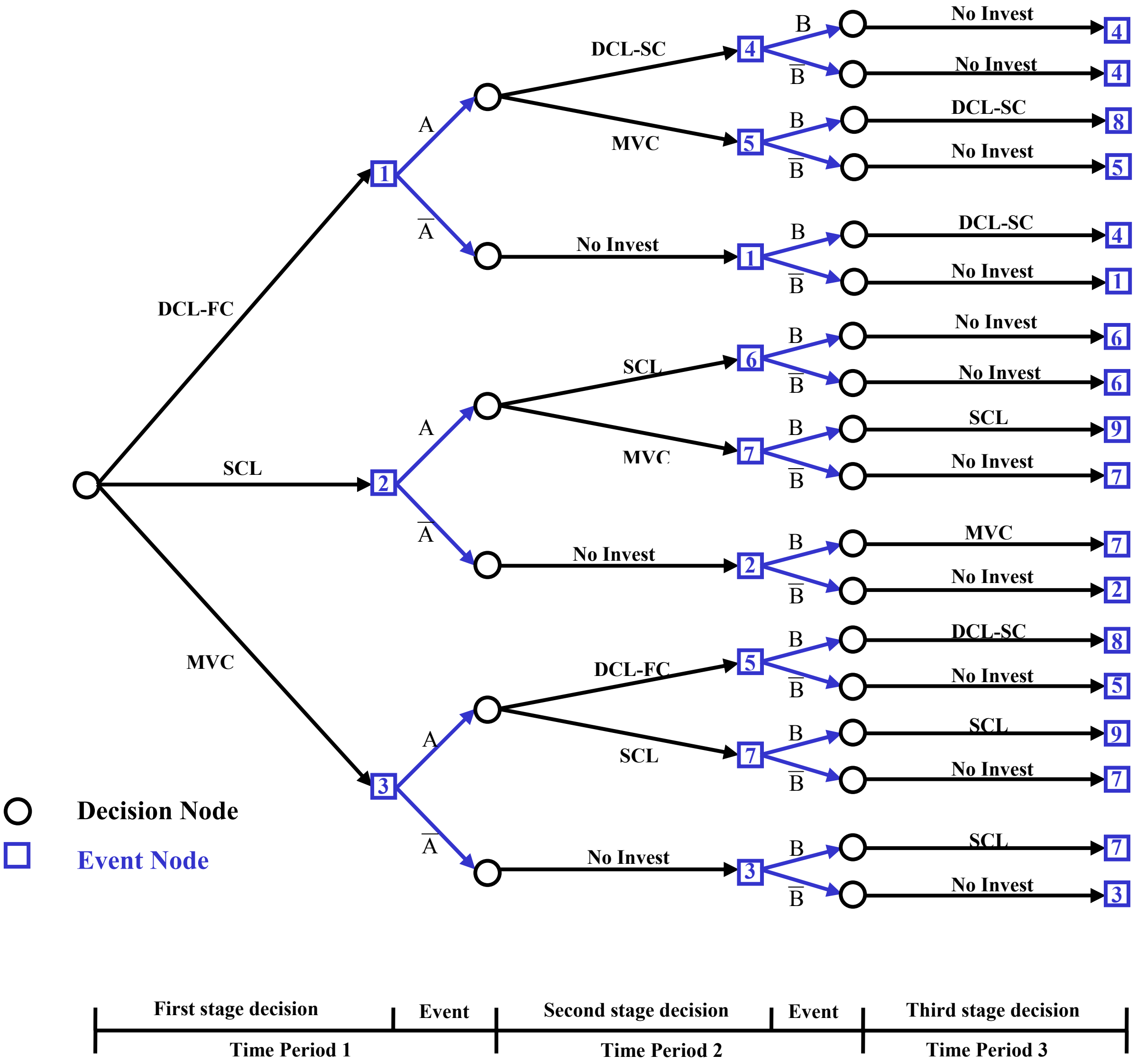


Fig. B.1 – Decision-event tree for expansion planning of the industrial network decisions to meat load A:

- second circuit of double-circuit line, or
- medium voltage cable.

If load A is not established, the decision "do nothing" is selected and so on.

To explain how the first optimal plan is selected, consider figure B.2 which shows a part of decision-event tree. Costs of expansion plans are specified inside parenthesis. This figure shows that if single-circuit line is built at the first stage of planning and if load A is established, we have two options at the beginning of year 5:

1) building another single-circuit line, and
2) building a medium voltage cable line.

If medium voltage cable line is built at the beginning of year 5 and if load B is added at beginning of year 7, another single-circuit line must be built to meet the load. As computed on the figure B.2, the expected cost of options 1 and 2 from the beginning of year 5 till end of

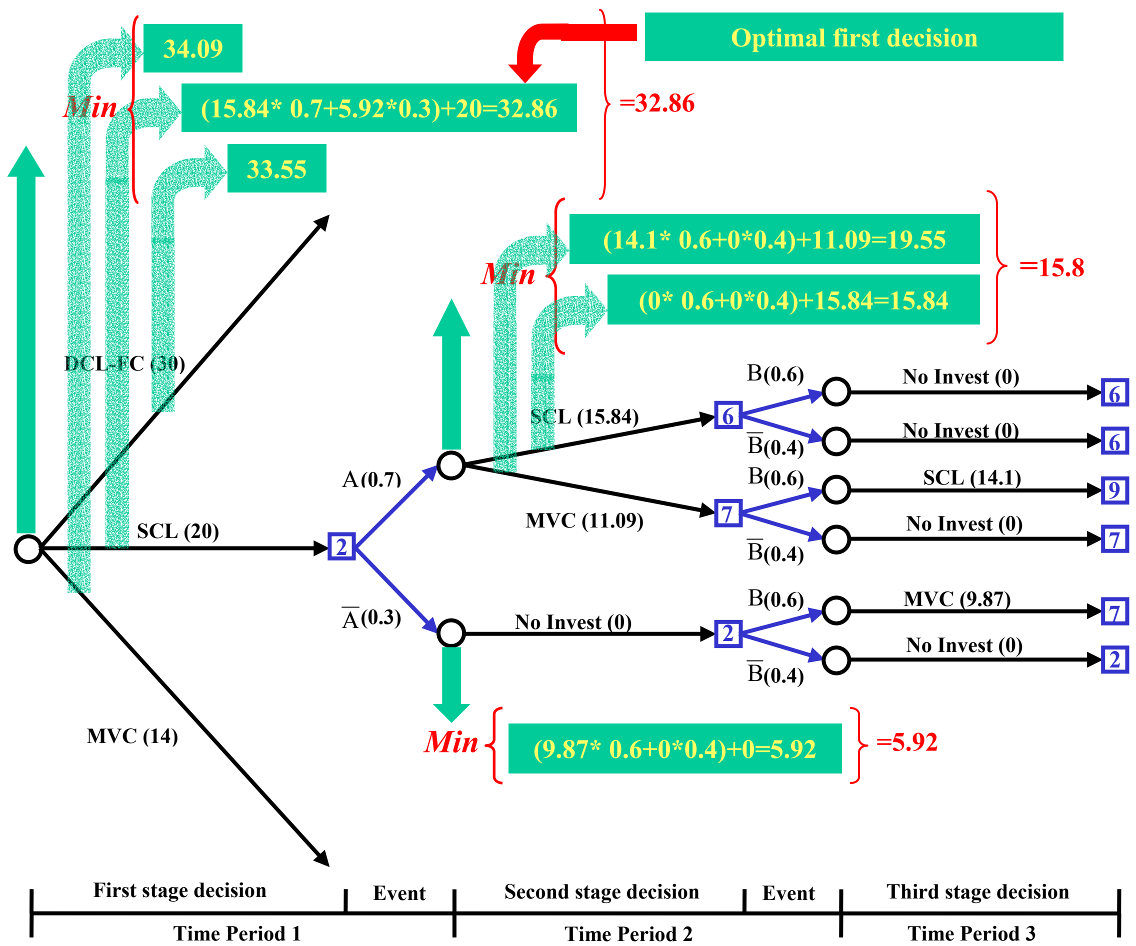


Fig. B.2 – Procedure of selecting the optimal first decision planning period is equal to 15.84 and 19.55. Hence, the minimum cost strategy i.e. building another single-circuit line at the beginning of year 5 is selected. If load A is not connected at the beginning of year 5, the expected cost of planning from the beginning of year 5 till the end of planning period is equal to 5.92, as computed on figure B.2. Therefore, if single-circuit line is built at the first stage of planning the expected cost of planning from the beginning of year 1 till the end of planning period is equal to 32.86, as shown in figure B.2. If double-circuit line with the first circuit is built at the first stage of planning, the expected cost of planning from the beginning of year 1 till the end of planning period is equal to 33.55, the process of computation is not shown in figure B.2. If medium voltage cable line is built at the first stage of planning, the expected cost of planning from the beginning of year 1 till the end of planning period is equal to 34.09. The minimum cost strategy at the first stage of planning is building a single-circuit line and is selected as the optimal first decision.

Appendix C: Examples for Locational Marginal Prices

Consider the 2 bus system which is shown in figure C.1. Data of transmission line and generators is given in tables C.1 and C.2. Locational marginal prices are computed for three different load conditions. Data of loads is given in table C.3.

Case 1:

Figure C.1 shows case 1. In this case, both loads can be supplied by the generator 1, which produces the cheapest power, without congesting the transmission line. If 1 MW load is added to bus 1 or 2, this 1 MW load is supplied by generator 1. Therefore, LMP of both buses is equal to the bid of generator 1 i.e. $10/MWhr.

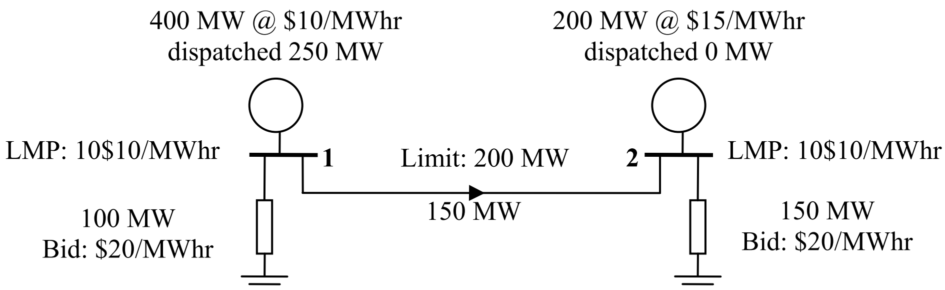


Fig. C.1- 2 bus system – case 1

Table C.1- Parameters of transmission line

From bus No.	To bus No.	Reactance (pu)	Limit (MW)
1	2	0.05	200

Table C.2- Data of generators

Bus No.	Min	Max (MW)	Bid ($/MWhr)
1	0	400	10
2	0	200	15

Table C.3- Data of loads for three different cases

Case	Bus No.	Min	Max (MW)	Bid ($/MWhr)
1	1	0	100	20
	2	0	150	20
2	1	0	100	20
	2	0	250	20
3	1	0	100	20
	2	0	250	12

Case 2:

Figure C.2 shows case 2. In this case, generator 1 can not supply both loads because of the transmission constraint. Hence, 50 MW of load 2 is supplied by the generator 2. If 1 MW load is added to bus 1, this 1 MW load is supplied by generator 1. Therefore, LMP of bus 1 is equal to \$10/MWhr. If 1 MW load is added to bus 2, this 1 MW load is supplied by generator 2. Therefore, LMP of bus 2 is equal to \$15/MWhr. Due to transmission congestion LMPs are not equal in this case.

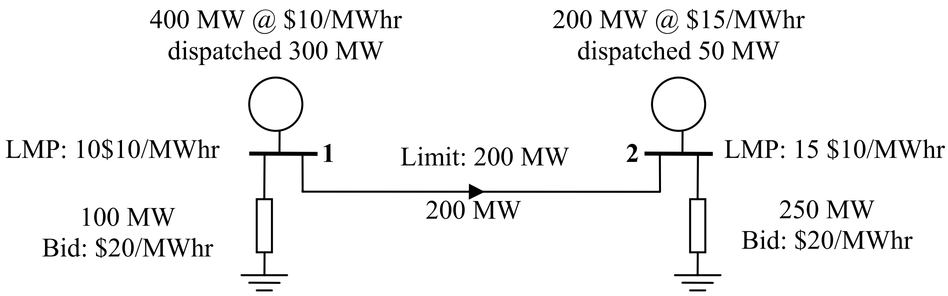


Fig. C.2- 2 bus system – case 2

Case 3:

In cases 1 and 2 LMPs of buses are smaller than bid of their loads. Hence, the loads are not curtailed. Case 3 is similar to case 2; except bid of load 2 is \$12/MWhr. Figure C.3 shows case 3. Due to transmission constraint, generator 1 can not supply more that 200 MW of load 2. If the rest of load 2 is supplied by generator 2, LMP of bus 2 will be \$15/MWhr (like case 2) which is greater than bid of load 2. Hence, load 2 is curtailed till LMP of bus 2 decreases to bid of load 2 i.e. \$12/MWhr. In fact each load can be modelled with a load which is curtailed never and an imaginary generator with the bid of load. For example, load of buses of 2 can be modelled with a 250 MW load and an imaginary generator with bid \$12/MWhr. The load is supplied fully and curtailed never. Figure C.4 shows the imaginary generator. In this case first generator of bus 1 is dispatched till reach transmission constraint. After that, imaginary generator is dispatched since its bid is smaller that bid of generator 2. If 1 MW load is added to bus 1, this 1 MW load is supplied by generator 1. Therefore, LMP of bus 1 is equal to \$10/MWhr. If 1 MW load is added to bus 2, this 1 MW load is supplied by imaginary generator. Therefore, LMP of bus 2 is equal to \$12/MWhr. The value of load curtailment is equal to dispatched value of imaginary generator. In this case, imaginary generator produces 50 MW. This means load of bus 2 is curtailed 50 MW, and only 200 MW of it is supplied. Because of the transmission congestions LMPs are not equal in this case.

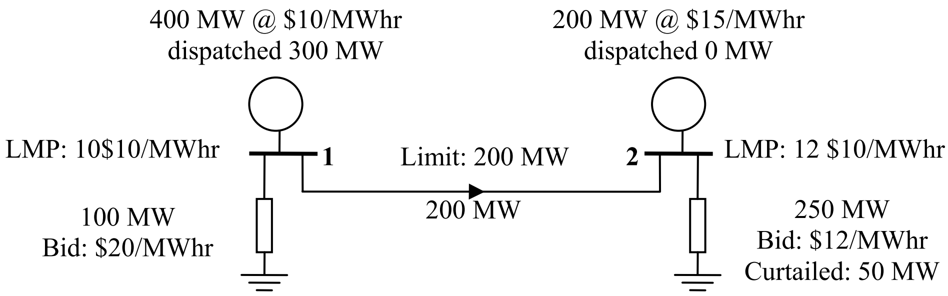


Fig. C.3- 2 bus system – case 3

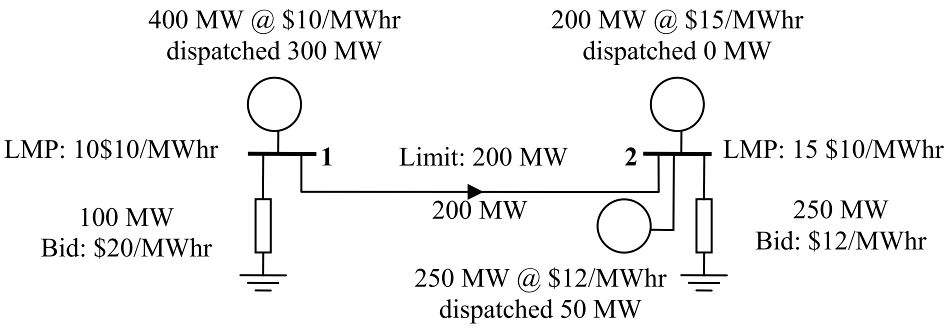


Fig. C.4- 2 bus system – modelling load 2 with a fix load and an imaginary generator

Appendix D: An Example on Computing Shadow Price

Consider the following optimization problem:

$$Max \quad J = 6x_1 x_2$$

$$s.t.: \quad 3x_1 + 4x_2 = 18$$

Lagrangian is equal to:

$$\mathcal{L} = 6x_1 x_2 - \lambda(3x_1 + 4x_2 - 18)$$

λ is called Lagrange multiplier or dual variable. Necessary conditions for extremum are:

$$\begin{cases} \dfrac{\partial \mathcal{L}}{\partial x_1} = 0 \\ \dfrac{\partial \mathcal{L}}{\partial x_2} = 0 \\ \dfrac{\partial \mathcal{L}}{\partial \lambda} = 0 \end{cases} \Rightarrow \quad \begin{cases} 6x_2 - 3\lambda = 0 \\ 6x_1 - 4\lambda = 0 \\ 3x_1 + 4x_2 = 18 \end{cases} \quad \Rightarrow \quad x_1^* = 3,\ x_2^* = 2.25,\ \lambda^* = 4.5,\ J^* = 40.5$$

Let to rewrite above constraint as follows:

$$3x_1 + 4x_2 = \mathrm{b}$$

then the Lagrangian is as bellows:

$$\mathcal{L} = 6x_1 x_2 - \lambda(3x_1 + 4x_2 - \mathrm{b})$$

Shadow price of a constraint is equal to the change in objective function per unit change in right hand side of the constraint, assuming all other constraints remain unchanged [65]-[66]. Shadow price of above constraint is equal to:

$$\left.\frac{\partial J}{\partial \mathrm{b}}\right|_{\text{at optimal point}} = \left.\frac{\partial \mathcal{L}}{\partial \mathrm{b}}\right|_{\text{at optimal point}} = \lambda^*$$

If b increases by 0.1 then:

$$\Delta J = \Delta b\ \lambda^* = 0.45 \qquad \Rightarrow \qquad J = 40.95$$

If the optimization problem is solved directly with b = 18.1, the same result will be archived.

Symbols

A_i^k	appropriateness degree of plan k versus ith risk assessment criterion
$\mathcal{A}_i^k$	appropriateness degree of plan k versus ith stakeholders' desire
$ANCC^k$	annual congestion cost of the network after adding plan k
$ANIC^k$	annual investment cost of plan k
$ANLP^k$	annual load payment after adding plan k
$ANOC^k$	annual operation cost of the network after adding plan k
$\mathbf{B}$	linearized Jacobian matrix
$\mathbf{C}_D$	vector of load bids
$\mathbf{C}_G$	vector of generator bids
$C_{d_{i,j}}$	bid of load i in the jth iteration of Monte Carlo simulation
$C_{g_{i,j}}$	bid of generator i in the jth iteration of Monte Carlo simulation
C_i^k	ith risk assessment criterion f plan k
$\mathcal{C}_i^k$	criterion for measuring ith stakeholders' desire
cc_i	congestion cost of line i
$cc_{i,j}^k$	congestion cost of line i after addition of plan k in the jth iteration of Monte Carlo simulation
$DANOC^k$	decrease in annual operation cost of the network after adding plan k
F_{ap}^k	fuzzy appropriateness degree (index) of plan k versus combination of all decision criteria in risk assessment
$\mathcal{F}_{ap}^k$	fuzzy appropriateness degree (index) of plan k versus combination of all decision criteria in measuring stakeholders' desires
$\mathcal{F}_{ap}^{k,l}$	fuzzy appropriateness index of plan k scenario l

$\mathcal{F}_{ap}^{op,l}$	fuzzy appropriateness index of optimal plan of scenario *l*
F_{ANCC}^{k}	decrease in annual congestion cost per unit of annual transmission cost of plan *k*
F_{ANLP}^{k}	decrease in annual load payment per unit of annual transmission cost of plan *k*
$F_{\sigma_{\mu_{lmp},w}}^{k}$	decrease in weighted standard deviation of mean of LMP per unit of annual transmission cost of plan *k*
$f^{k,l}$	cost function (goodness measuring criterion)of plan *k* in scenario *l*
$f^{op,l}$	cost function of the optimal plan of scenario *l*
$\mathbf{H}$	matrix of linearized line flows
$\mathrm{J}(\mathbf{P}_G, \mathbf{P}_D)$	total operation cost
$lmp_{i,j}^{k}$	LMP of bus *i* after adding plan *k* in the *j*th iteration of Monte Carlo simulation
N_b	number of buses
N_c	number of decision criteria
N_d	number of loads
N_g	number of generators
N_l	number of transmission lines
N_p	number of expansion plans
N_r	number of Monte Carlo iteration
N_{sc}	number of scenarios
N_{sd}	number of stakeholders' desires
N_{st}	number of stakeholder groups
N_i^k	normalized appropriateness degree of plan *k* versus decision criterion *i* in risk assessment
$\mathcal{N}_i^k$	normalized appropriateness degree of plan *k* versus decision criterion *i* in measuring stakeholders' desires
P_{Base}	base of active power
$P_{c\ i,j}^{k}$	amount of curtailment of load *i* after adding the plan *k* in the *j*th iteration of Monte Carlo simulation
$\mathbf{P}_{\mathrm{D}}$	vector of active loads
$\overset{\min}{\mathbf{P}_D},\ \overset{\max}{\mathbf{P}_D}$	vectors of minimum and maximum loads limits

P_{d_i}	load at bus i
$P^k_{d\,i,j}$	load of bus i after addition of plan k in the jth iteration of Monte Carlo simulation
$\mathbf{P}_G$	vector of active power generations
$\mathbf{P}^{\min}_G$, $\mathbf{P}^{\max}_G$	vectors of minimum and maximum active power generation limits
P_{g_i}	generation power at bus i
$P^k_{g\,i,j}$	generation power of bus i after addition of plan k in the jth iteration of Monte Carlo simulation
$P^k_{l_{i_1 i_2},j}$	power of line i which flows from bus i_1 to bus i_2 after adding plan k in the jth iteration of Monte Carlo simulation
$\mathbf{P}^{\max}_\ell$	vector of line limits
$\mathbf{P}_{tie}$	vector of output power from the tie-lines
$R^{k,l}$	fuzzy regret of plan k in scenario l
$r^{k,l}$	regret of plan k in scenario l
T_{Peak}	total peak load time per year
tcc	total congestion cost of the network
tcc^k_j	total congestion cost of the network after adding plan k in the jth iteration of Monte Carlo simulation
U_i	importance degree of desire i from the viewpoint of transmission planners
Z^l	fuzzy occurrence degree of scenario l
W_i	fuzzy importance weight of decision criterion i
w^k_i	weight of bus i after adding plan k
X_j	fuzzy importance weight of stakeholder j in decision making
Y_{ij}	fuzzy importance degree of desire i from the viewpoint of stakeholder j
δ	vector of voltage angles
λ	Lagrange multiplier
μ^k_{lcc}	average load curtailment cost after adding plan k
$\mu^k_{lmp_i}$	mean of LMP of bus i in the presence of plan k
μ^k_{lmp}	average LMP of the network

$\mu^k_{P_{d_i}}$	mean of load at bus *i* after adding plan *k*
$\mu^k_{P_{g_i}}$	mean of generation power at bus *i* after adding plan *k*
$\mu^k_{(P_{g_i}+P_{d_i})}$	mean of sum of generation power and load at bus *i* after adding plan *k*
μ^k_{rgc}	average cost of running generators after adding plan *k*
μ^k_{tcc}	average of total congestion cost of the network in the presence of plan *k*
μ^k_{tlp}	average of total load payment during the peak load of planning horizon after adding plan *k*
υ^l	occurrence degree of scenario *l*
$\sigma^k_{\mu_{lmp}}$	standard deviation of mean of LMP in the presence of plan *k*
$\sigma^k_{\mu_{lmp},w}$	weighted standard deviation of mean of LMP with the weight w in the presence of plan *k*

Abbreviations

ACC	Average Congestion Cost
ALP	Average Load Payment
IPP	Independent Power Producer
ISO	Independent System Operator
LMP	Locational Marginal Price
PDF	Probability Density Function
PJM	Pennsylvania -New Jersey – Maryland
SML	Standard deviation of Mean of LMP
SV	Specified Value
WD	standard deviation of mean of LMP Weighted with mean of Demand
WG	standard deviation of mean of LMP Weighted with mean of Generation power
WGD	standard deviation of mean of LMP Weighted with mean of sum of Generation power and Demand

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Zusammenfassung

Das Hauptziel dieser Arbeit ist, eine zentralisierte statische Vorgehensweise für die Erweiterungsplanung von Übertragungsnetzen in deregulierten Energie Systemen aufzubauen. Die Umstrukturierung und die Deregulierung haben die Rollen der Interessenvertreter des Netzes entkoppelt, und die Übertragungsnetzplaner werden neuen Zielsetzungen und Unsicherheiten ausgesetzt. Das so genannte „Unbundling“ der Aufgaben bringt neue Herausforderungen für die Interessenvertreter der Netze. Sie haben in diesem Umfeld unterschiedliche Wünsche und Erwartungen an das Verhalten und die Erweiterung des Systems. Folglich sind neue Aufgaben hinsichtlich der Entscheidungsfindung für die Erweiterung der Übertragungsnetze aufgetreten. Die vorliegende Arbeit betrachtet die neuen Zielsetzungen und die Unsicherheiten der Erweiterungsplanung des Übertragungsnetzes.

Diese Arbeit wird in sechs Hauptteilen behandelt. Im ersten Teil wird ein Wahrscheinlichkeitswerkzeug für die Analysierung der Leistung der elektrischen Märkte dargestellt. In diesem Teil werden Wahrscheinlichkeitsdichtefunktionen der lokalen Grenzpreise des elektrischen Marktes berechnet. Die Vorgehensweise wurde an einem Acht-Knoten-Netz angewendet. Die Einflüsse von Lastreduzierung und Durchleitung auf den Leistungspreis am Knoten wurden nachgebildet. Die Untersuchung zeigt, daß die Durchleitungsverträge die lokalen Grenzpreise der Netze beeinflussen. Es zeigt sich auch, daß die Durchleitungsverträge in bestimmen Richtungen die Netzengpassung verringern und Erweiterung des Übertragungsnetzes hinausschieben können.

Im zweiten Teil werden zwei Marktkriterien dargestellt, um festzustellen, ob ein Erweiterungsplan den Wettbewerb erleichtert und fördert. Die Kriterien sind „durchschnittliche Engpassungskosten“ und „gewichtete Standardabweichung des Mittelwerts der lokalen Grenzpreise“. Unterschiedliche Gewichte werden benutzt, um ein wettbewerbsfähiges Umfeld mehreren Teilnehmern am Energiesystem zur Verfügung zu stellen. Die Festlegung der Kosten ist in einem wettbewerbsfähigen Umfeld sehr wichtig.

Folglich sind die dargestellten Kriterien um Netzerweiterungskosten ergänzt, zu betrachten.

Im dritten Teil der Arbeit wird eine Erweiterungsplanung für Übertragungsnetze im deregulierten Umfeld dargestellt. Diese Vorgehensweise besteht aus der Szenariotechnik und dem wahrscheinlich optimalen Leistungsfluss, der im ersten Teil dargestellt wurde. Die Szenariotechnik wird verwendet, um die nicht-zufälligen Unsicherheiten in Betracht zu ziehen. Der wahrscheinlich optimale Leistungsfluss wird verwendet, um die zufälligen Unsicherheiten zu betrachten. Die Berechnung verwendet wettbewerbsfähige Kriterien, um die Güte der Erweiterungspläne zu messen, und Sie ermöglichen ein nicht diskriminierendes wettbewerbsfähiges Umfeld für die Netzteilnehmer. „Minimax Regret“ wird in der Szenariotechnik für die Risikobeurteilung und die Vorauswahl des abschließenden Planes verwendet. Um festzustellen, welches Kriterium zu keinen Engpassungskosten und einem Flachpreisprofil mit minimalen Kosten oder mit minimalen Erweiterungsplänen führt, wurde die dargestellte Vorgehensweise an dem IEEE 30-Knoten-Netz angewendet.

Die konventionelle Risikobeurteilung hat einige Mängel. Im vierten Teil werden die Mängel der Szenariotechnikkriterien herausgestellt, und neue Kriterien werden für die Szenariotechnik definiert. Fuzzy-Multi-Kriterienentscheidungen werde für die Risikobeurteilung der Lösungen verwendet. In dieser Methode wird ein „Fuzzy Index“ für die Vorauswahl des abschließenden Planes definiert. Der „Fuzzy Index“ wird durch Zusammenfassung der Wichtigkeitsgrade der Entscheidungskriterien und der Angemessenheitsgrade der Erweiterungspläne gegenüber den Entscheidungskriterien ermittelt. Die dargestellte Vorgehensweise wird anhand des IEEE 30-Knoten-Netzes gezeigt. Das Resultat wurde mit der konventionellen Risikobeurteilung bei unterschiedlichen Fällen verglichen. Der Vergleich zeigt, daß die Fuzzy-Risikobeurteilung die Mängel der konventionellen Risikobeurteilung aufhebt.

Im fünften Teil der Arbeit wird eine Erweiterungsplanung für Übertragungsnetze, basierend auf den Wünschen der Netzinteressenvertreter, dargestellt. Die Vorgehensweise betrachtet in der Netzerweiterungsplanung die Wünsche der Kunden, der Energieerzeuger, der Netzeigener, der Netzbetreiber und des Regulators. Die Wünsche der Netzinteressenvertreter sind Z.B.: Wettbewerb, Zuverlässigkeit, Flexibilität, Netzentgelte und Umwelteinfluß. Fuzzyentscheidungen berücksichtigen die Wünsche aller Netzinteressenvertreter und ein „Fuzzy Index“ wird für das Messen der Güte der Ereiterungspläne definiert. Der „Fuzzy Index“ wird aus der Zusammenfassung der Wichtigkeitsgrade der Netzinteressenvertreter, der Wünsche der Netzinteressenvertreter aus deren Gesichtspunkt, und dem Grade der

Übereinstimmung der Erweiterungspläne in Abhängigkeit von den Wünschen der Interessenvertreter der Netze ermittelt. Die Vorgehensweise wurde auf das IEEE 30-Konten-Netz angewendet.

Die dargestellte Vorgehensweise im fünften Teil ist nur in der Lage zufällige Unsicherheiten zubetrachten. Im sechsten Teil wird die dargestellte Vorgehensweise um Wünsche der Interessenvertreter des Netzes mit nicht-zufälligen Unsicherheiten erweitert. Ein „Fuzzy Index“ wird definiert, um die Güte jedes Erweiterungsplans in jedem Szenario basierend auf den Wünschen der Netzinteressenvertreter zu messen. „Fuzzy Regret“ wird mit dem Betrachten der Eintrittswahrscheinlichkeit Auftretengrade der zukünftigen Szenarios definiert. „Fuzzy Regret“ von Plan k in Szenario *l* ist die Differenz zwischen dem „Fuzzy Index“ von Plan k in Szenario *l* und dem „Fuzzy Index“ des optimalen Planes von Szenario *l*. Eine Fuzzy-Risiko-Bewertung wird angewendet, um den endgültigen Plan zu ermitteln. Die Realisierungsschritte werden unter Berücksichtigung des Acht-Knoten-Netzes im Detail beschrieben.

Es ergeben sich folgende Resultate. Die Kriterien „durchschnittliche Engpassungskosten“ und „gewichtete Standardabweichung des Mittelwerts der lokalen Grenzpreise“ mit der Wichtung „Summe des Mittels der Erzeugung und der Last“ sind die besten Kriterien zur Förderung eines wettbewerbsfähigen elektrischen Marktes. Das Kriterium „Durchschnittliche Engpassungskosten“ ist unempfindlicher als die anderen Kriterien zu der Eintrittswahrscheinlichkeit der zukünftigen Szenarios. Die Fuzzy-Risikobeurteilung hebt die Mängel der konventionellen Risikobeurteilung auf.

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